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Household carbon footprint patterns by the degree of urbanisation in Europe

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Abstract

Urbanisation increases household carbon footprints in developing economies. However, the results from developed countries have varied, particularly in Europe. This study provides a coherent comparison of the impact of the degree of urbanisation on income, expenditure and carbon footprints in Europe. On average, carbon footprints are 7% lower in cities than in rural areas when income and household characteristics are controlled. However, this is compensated by the 6% higher average income in cities. The patterns are not uniform in all countries. In Eastern Europe, the pattern is similar to other developing regions. In some Western European countries, both the income level and the carbon footprints are lower in urban areas than in rural areas. In the rest of Europe, the differences in income level between rural and urban areas are small, but they still largely compensate for the efficiency benefits of urban areas. We call for more systemic emissions accounting and climate strategies.

Introduction

In Europe, almost three quarters of the population live in urban areas, and the percentage is constantly growing. The increasing urban population has important implications for the environmental impacts caused by Europeans. It requires investments in new residential construction, infrastructure and services. Urban areas concentrate economic activities, which increases the income level of the citizens. At the same time, consumption patterns (Shigeto *et al* 2012, Millward-Hopkins *et al* 2017), time-use (Wiedenhofer *et al* 2018) and lifestyles (Heinonen *et al* 2013, Zhang *et al* 2016) may change towards typical metropolitan behaviour. All of the above have environmental consequences.

The impact of urban development on total energy requirements (Pachauri 2004, Lenzen *et al* 2006, Wiedenhofer, Lenzen and Steinberger 2013) and carbon footprints, meaning consumption-based greenhouse gas (GHG) emissions, has interested many researchers. Previous literature has revealed that since the demand of goods and services in cities is a significant driver of global environmental impacts, it is important to take into account the transboundary resource and emission flows (Ramaswami *et al* 2012, Schubert and Gill, 2015, Wiedmann 2016, Fry *et al* 2018). Consumption-based accounting (CBA) that captures these flows is gaining interest not only in research, but also in policy making (Barrett *et al* 2013, Afionis *et al* 2017, Ottelin *et al* 2019).

There have been several ways to approach the relationship between urban development and consumption-based carbon footprints in the previous literature. The scope of the included emissions, the studied urban variables and the methods vary. In particular, there are actually two types of consumption-based carbon footprints (and their hybrids), which differ significantly in their scope (Usubiaga and Acosta-Fernández 2015, Owen 2017, Ottelin *et al* 2019). First, carbon footprints can be assessed by using national or regional accounts directly. In this case, public consumption and investments are usually included in the assessment. In addition, national and regional accounts are usually based on geographical boundaries and thus include both the consumption of the residents and the visitors within the boundaries. However, residents' consumption abroad is typically excluded. Second, it is possible to focus on the residents of the area. The personal or residential carbon footprints cover the consumption-based emissions of the residents, irrespective of where the consumption takes place (Heinonen *et al* 2013). Personal carbon footprints are typically assessed by using household budget surveys, which excludes public consumption and investments. The difference between the two consumption-based carbon footprints of the same area can be significant (>50%), particularly in countries with rapid urbanisation, such as China (Ottelin *et al* 2019).

Studies on a detailed spatial scale, for example neighbourhood level, practically always study personal carbon footprints, because national and regional accounts cannot be applied. Several of these studies have compared the absolute carbon footprints between urban, suburban and rural areas (Minx *et al* 2013, Ottelin *et al* 2015, Maraseni *et al* 2016, Zhang *et al* 2016, Wiedenhofer *et al* 2018). The majority of these studies have found the highest carbon footprints in the most urbanised areas. However, the studies highlight that it is the socio-economic variation rather than the degree of urbanisation that matters (Minx *et al* 2013, Ottelin *et al* 2015).

It is also common to use regression analysis or similar to control for socio-economic and other variables in order to examine the impact of the urban variable separately. Several studies have found that the carbon footprint decreases with the increasing degree of urbanisation when income is controlled, but the location of the study affects the results. Studies from the US have often found a decreasing impact (Shammin *et al* 2010, Jones and Kammen 2014, Fremstad *et al* 2018, Underwood and Fremstad 2018), whereas studies from developing countries have found the opposite (Zhang *et al* 2016, Liu *et al* 2017, Seriño 2017). The results from Europe vary, but the majority of the studies have found a small decreasing impact for an increasing degree of urbanisation, for example in the UK (Minx *et al* 2013), Finland (Ala-Mantila *et al* 2014), Sweden (Nässén *et al* 2015) and Germany (Gill and Moeller 2018). Some studies from Finland and Estonia highlight that the impact is largely statistically insignificant (Ottelin *et al* 2015, Poom and Ahas 2016, Ottelin *et al* 2018b). Similarly, Ivanova and colleagues found in their study of 27 EU countries that the impact of the degree of urbanisation on the carbon footprint is insignificant in the EU overall (Ivanova *et al* 2017).

Zhang and co-authors provide a valuable discussion on the need for more sophisticated models to capture and classify the different impacts of urbanisation on the carbon footprint (Zhang *et al* 2016). They distinguish between purposeful socio-demographic changes and changes in human settlements, such as infrastructure. They argue that increasing income and employment are purposeful outcomes of rural-to-urban migration. Thus, in order to compare the carbon footprints of rural residents to those of rural-to-urban migrants, they use a combination of propensity score matching and regression analysis to study separately the urban migration effect and urban settlement effect. Similarly, Ottelin (2016) suggests that controlling income in order to compare the carbon footprints of rural- and metropolitan residents is questionable, since metropolitan areas have significantly better job opportunities and a higher wage level, which are drivers of the residents' income (making it an endogenous variable). However, controlling income in order to study the impact of urban structure is meaningful if the scope of the study is a single working district, such as a metropolitan area, where residential location does not affect job opportunities, as in (Lenzen *et al* 2004, Ornetzeder *et al* 2008, Ottelin *et al* 2018b), for example.

There are time-series studies on carbon footprints as well that include variables related to urbanisation. The majority of these studies are from China; they describe how urbanisation has been connected to economic growth and increasing carbon footprints during the past decades (Fan *et al* 2012, Liu *et al* 2017, Wiedenhofer *et al* 2017). There are fewer such studies from the European context. Druckman and Jackson (2009), and Millward-Hopkins and colleagues (2017) provide time-series analyses on carbon footprints from the UK, Nässén (2014) from Sweden, and Ottelin and colleagues (Ottelin *et al* 2018b) from Finland. However, these studies do not aim to isolate the impacts of urbanisation, but examine the changes over time at a more general level.

Another issue is that the majority of the existing studies on the relationship between the degree of urbanisation and the carbon footprint focus on single countries, which restricts the generalisability and comparability of the results due to differences in methods and scopes. While Ivanova and co-authors (2017) provide a valuable overview on the European carbon footprints, the aspects of urbanisation are not in the focus of their study.

The purpose of this study is to provide a comprehensive and coherent view of the household carbon footprint patterns by the degree of urbanisation in Europe, and thus to clarify the current contradictions in the literature regarding the impact of the level of urbanisation on carbon footprints in developed countries. We demonstrate the simultaneous impacts of the degree of urbanisation on income, expenditure and carbon footprints in 25 EU countries by comparing the residents of cities, towns and rural areas. The country-specific results allow us to analyse the differing patterns that can be found particularly between Eastern Europe, where the transformation from an agrarian society to an industrial society is still ongoing, and the rest of Europe.

For research material, we use the Eurostat's Household Budget Survey (HBS) 2010 (Eurostat 2010) and a multi-regional input–output (MRIO) model, Eora26, developed by Lenzen and colleagues (2012, 2013). Thus, we include household consumption, but exclude public consumption and public investments (gross fixed capital formation). From this point on, we refer to this carbon footprint of household consumption per capita as the 'carbon footprint'.

Materials and methods

EE IO analysis

The carbon footprints were calculated with an environmentally extended economic input–output (EE IO) analysis, which is an established method to assess consumption-based carbon footprints (Leontief 1970, Lenzen *et al* 2014). The method is based on monetary transaction matrices between economic sectors. For an introduction to the method, see (Murray and Wood 2010, Kitzes 2013, Murray and Lenzen 2013). Owen (2017) provides a recent deeper introduction, particularly to MRIOs. Single-region (SRIO) models include the economy of one region, usually a country, whereas MRIO models cover several regions—the whole global economy in the best case. SRIO models suffer from the domestic technology assumption, meaning that imported products are assumed to be produced with the same technology as domestic products. MRIO models are more accurate in this respect, since the starting point is the actual territorial emissions of each country and economic sector (Lenzen *et al* 2014).

Materials

The main research materials of the study are the Eurostat's Household Budget Survey (HBS) 2010 (Eurostat 2010) and a publicly available (http://worldmrio.com/) multi-regional input–output (MRIO) model, Eora26, developed by Lenzen and colleagues (2012, 2013). Eurostat's HBS are conducted by all EU member states around every five years. Their main purpose is to provide information about household's expenditure and living conditions. The HBS microdata includes 244 000 households in 25 countries. The sample sizes for each country are provided in the supplementary information, in the 'Results by country' -section. HBS contains detailed data on household expenditures, classified according to the UN's COICOP classification (Classification of Individual Consumption by Purpose). In addition, the HBS includes socio-economic and demographic information on household members, and geographic information about the location of the households. In particular, the degree of urbanisation of the residential location of each household is included. Although there is a continuous aim to harmonise the HBSs (regarding the used variables, survey methods, and survey years) in the EU, it is acknowledged that there are still differences in data collection and processing between the countries (Eurostat 2018c).

The Eora26 is a MRIO model that includes 187 countries, 26 economic sectors, time-series from 1990 to 2015, and 2720 environmental and economic indicators. In the study, we used the PRIMAP-hist dataset (Gütschow *et al* 2017) for greenhouse gas (GHG) emissions. The PRIMAP-hist is a comprehensive dataset that combines several published datasets on territorial GHG emissions, including EDGAR (http://edgar.jrc.ec.europa.eu/). It covers all 196 member states of the UNFCCC (United Nations Framework Convention on Climate Change). All Kyoto GHGs are included, separately and combined. The included emission categories are: Total energy (CAT1), Industrial processes (CAT2), Solvent and other process use (CAT3), Agriculture (CAT4), Land-use and land-use change (LULUCF) (CAT5), Waste (CAT6) and Other (CAT7). PRIMAP-hist does not include emissions from international aviation and shipping of goods and services. For more details, see Gütschow *et al* (2016).

Carbon footprint model of the study

In the study, we used the simplified version of the full Eora model, Eora26. We calculated the consumption-based GHG intensities of the 26 economic sectors of each country. In order to match the sectoral intensities with the COICOP sectors in the Eurostat's HBS, we compared the household final consumption between Eora and the HBS. The comparison and matching of Eora and the HBS are presented in supplementary tables 19 and 20.

The Eora model has been balanced to create a consistent global model. Because of inconsistencies in the original data, the results of small countries may in some cases become distorted during the balancing process (Eora FAQ: http://worldmrio.com/documentation/faq.jsp). We noticed this because in some cases the consumption-based GHG intensities were negative, which is unlikely in reality. In reality, this can only occur if the land-use change leads to decreasing emissions in some sector, and this impact from sequestration is passed on through the supply chain all the way to the final demand. This did not seem to be the case in the study, and thus we replaced the negative sectoral intensities with the sectoral intensity of the neighbouring or similar country. These were minor changes that do not significantly affect the results. However, the results in small countries should in general be interpreted cautiously.

The consumption-based GHG intensities of commodities calculated with the EE IO analysis do not include the direct GHG emissions of households, nor the emissions caused by passenger air travel. Thus, we added the combustion-phase emissions of motor fuels, air travel and housing energy to our carbon footprint model. We calculated the motor fuel consumption by using the European Commission's statistics on fuel prices (EC 2018).

In the case of air travel, we used estimates from the European Aviation Safety Agency's (EASA) 'Environmental Report 2016' for CO_2 emissions and fuel consumption per passenger kilometre (EASA 2016). We estimated the climate impact of other GHGs and contrails by using a multiplier of 1.4 for CO_2 emissions. We derived the multiplier from the studies by Aamaas and colleagues (2013) and Czepkiewicz and colleagues (2018). The estimated multiplier is quite conservative. For comparison, Lee and co-authors, in their comprehensive analysis, estimated aviation impact multipliers ranging from 1.3 to 4.8 (Lee *et al* 2010). We added the upper-tier (production chain) emissions for aviation fuels by using the Eora's petroleum sector. In order to convert the expenditure data into passenger kilometres, we used European Commission's report 'Annual Analyses of the EU Air Transport Market 2016' (EC 2017). The estimate is 14.1 pkm/€ in 2010. In the case of package holidays, we allocated half of the expenditure for flying and the other half for accommodation. We excluded the other life cycle emissions related to air travel, such as airports and the production of airplanes. These emissions are assumed to be low, similarly as in a recent study on the carbon footprint of global tourism (Lenzen *et al* 2018). Although our estimates regarding air travel include a lot of uncertainties, such as price differences in flight tickets, these should be largely cancelled out because of the large sample size of the study. However, there is a more profound limitation in the HBS itself. Some countries have suspiciously low expenditure on flights and holiday travel in general, which is likely due to problems in the original survey questions. In future HBSs, it would be important to ask the expenditure on flights and package holidays during the whole year, instead of a shorter period of time. Furthermore, some countries have excluded consumption abroad, which leads to a significant underestimation of the emissions of holiday travel (Lenzen *et al* 2018). On the other hand, some countries, such as Belgium and Denmark, already have very frequent data on holiday travel in the HBS. We took these differences into account in the interpretation of the results.

We used the European Environment Agency's (EEA) statistics on the GHG intensity of electricity production (EEA 2018) to calculate the emissions caused by household electricity consumption. We used the average GHG intensity of EU countries, 302 CO_2 g kWh^{-1} in 2010, for countries that have little domestic production and mainly import electricity: Croatia, Latvia, Lithuania and Luxembourg. Otherwise, we used the average GHG intensity of the domestic electricity production, which varied from 20 CO_2 g kWh^{-1} in Sweden to 880 CO_2 g kWh^{-1} in Greece in 2010. In the case of heating energy, we assumed it is all natural gas. We had to make this assumption, since the Eurostat statistics on housing energy prices only include electricity and gas prices (Eurostat 2018b). We used country-specific prices for electricity and natural gas, and GHG intensity of 198 g kWh^{-1} for the latter. We calculated the electricity and heat consumption (kWh) separately for each household by using the expenditure data and the country-specific prices. The HBS includes separately the expenditure on electricity and heat. An important limitation regarding housing energy is that HBS only includes energy that households buy directly. Energy consumption that is included in rentals and imputed rentals is not included in the carbon footprint model of the study. This is particularly problematic in the cases of Denmark, Sweden and Finland, where apartment buildings mainly use district heating that is typically not bought directly by households but by housing companies. The component embedded in rental payments may be present throughout Europe as well.

Following the Eora model, we used the GHG intensity of 'Financial Intermediation and Business Activities' for rentals and imputed rentals (see supplementary table 19). The GHG emissions of this sector largely include emissions of new construction and financial services, but not the energy consumption of residential buildings. Although the rentals and imputed rentals do not necessarily reflect very well the GHG emissions of construction at the household level, they do reflect the concentration of new construction in large cities and other centres of growth quite well. However, the overall GHG intensity of the financial sector is very low, 0.2 CO_2-eq kg/€ on average (supplementary table 20). Thus, despite their significant share of household consumption, rentals and imputed rentals compose only a small part of the total carbon footprint. In the figures and tables, we have combined the housing finance and construction with housing maintenance, which includes GHG emissions caused by maintenance and repair of the dwelling and miscellaneous services related to the dwelling (COICOP categories 043 and 044).

Multivariable regression analysis

We studied the impact of the degree of urbanisation on carbon footprints with multivariable regression analysis. The general model used in the study is derived from the previous literature (Lenzen *et al* 2004, Weber and Matthews 2008, Ala-Mantila *et al* 2014) as follows:

$$\begin{aligned}\ln(\mathrm{CF}) = {} & \beta_0 + \beta_{\mathrm{E}} \ln(\mathrm{Income}) + \beta_{\mathrm{n}}\mathrm{HHS}_{\mathrm{n}} \\ & + \beta_1 \mathrm{Small\_children} + \beta_2 \mathrm{School\_children} \\ & + \beta_3 \mathrm{Young} + \beta_4 \mathrm{Seniors} + \beta_{\mathrm{m}} \mathrm{Urban}_{\mathrm{m}} + u,\end{aligned}$$

where CF is the carbon footprint; income is disposable income (€) per capita; HHS is household size; Small children, School children, Young and Seniors are dummy variables; Urban is the degree of urbanisation; u is error term, and betas are regression coefficients. Income and household size are the main drivers of carbon footprint. In the study, we run separate regression analyses for each country, as well as an analysis for the full dataset. In the case of the full dataset, we control for the country. This controls for all country-specific characteristics, such as differences in production technologies and consumer markets (which affect the GHG intensities of COICOP categories), but also differences in the collection and processing of the HBS data. If we had not control for the country, the results would be biased. For example, the rural population of the EU concentrates in countries with a low income level, and thus the model would compare low income countries to high income countries rather than the urban and rural populations that we are interested in for the study. In order to save space, we do not show the regression coefficients of the countries in the tables. In any case, we would recommend not using the coefficients to compare the countries with each other, but only to compare the results within each country. This was not the focus of the study, and we do not provide any deep analysis on the differences in the data quality between the countries.

It should be noted that due to the log transformation, the regular regression model only includes households that have expenditures in the studied consumption category. The model excludes zeros, however. This is problematic in the case of other travel and private transport, since a significant share of households have no expenditure on these categories in the HBS. The surveys are often conducted so that they only cover expenditures during 2 or 4 weeks, which is particularly problematic in the case of holiday travel. Thus, in addition to the regular regression model, we run logit models (logistic regression) for driving, i.e. P(CF private transport > 0) and holiday travel, i.e. P(CF holiday travel > 0). Holiday travel comprises the majority of the carbon footprint of other travel. The logit model used is as follows:

$$P(\text{CF commodity } n > 0) = F(\beta_0 + \beta_E \ln(\text{Income}) + \beta_n \text{HHS}_n + \beta_1 \text{Small\_children} + \beta_2 \text{School\_children} + \beta_3 \text{Young} + \beta_4 \text{Seniors} + \beta_m \text{Urban}_m + u,$$

where $F(z) = \mathrm{e}z/(1 + \mathrm{e}z)$ is the cumulative logistic distribution.

We followed Ala-Mantila *et al* (2014) and used STATA's survey settings in all our analyses. This allows including the survey weights in the regression models, which is important when using demographic survey data. The weights correct the demographic differences between the sample and the population under examination. For example, seniors are overrepresented in HBSs, and weights are used to correct this bias. Similarly, the sample sizes vary by country and population weights are needed to study the European averages. We used the weights provided by the Eurostat HBS throughout the study. We multiplied the weights by the household size in order to have per capita as the unit of analysis. In order to quantify the severity of multicollinearity, we calculated variance inflation factors (VIF) for the main regression models (Models 1a-b, Model 5). For Models 1a-b, they were below 4 for all variables, except for two countries in the categorical country variable. For Germany and Poland VIFs varied from 6.2 to 6.7. We considered this acceptable, since excluding the country variable would have led to a serious bias (see above). For Model 5, which includes education and occupation, VIFs were below 6 for all variables. For the variable of interest, the degree of urbanization, VIFs were below 2 in all models. Usually VIFs above 10 are considered problematic. We run separate models for income and expenditure throughout the study, because they cannot be included in the same model due to collinearity.

The degree of urbanisation and the EU regions

In the study, we measure urbanisation as the degree of urbanisation defined by Eurostat. The degree of urbanisation classifies local administrative units into three types of area: cities (densely populated areas), towns and suburbs (intermediate density areas) and rural areas (thinly populated areas). The classification was revised and harmonised in 2011, to take into account the total population of the area (Eurostat 2018a). However, in HBS 2010, the classification is based solely on the population density of the local administrative units. Cities have at least 500 inhabitants km^{-2}, towns and suburbs have 100–499 inhabitants km^{-2} and rural areas have less than 100 inhabitants km^{-2}.

In addition, we divided the studied countries into four regions. Northern Europe includes Denmark, Sweden, Finland and Estonia. Western Europe includes Belgium, Germany, France, the UK, Ireland and Luxembourg. Eastern Europe includes Bulgaria, Czech Republic, Hungary, Latvia, Lithuania, Poland, Slovenia and Slovakia. Southern Europe includes Spain, Italy, Greece, Portugal, Croatia, Malta and Cyprus. The Netherlands, Austria and Romania were excluded from the study due to the lack of data.

Results

Carbon footprints by the degree of urbanisation

The average carbon footprint tends to increase from rural to urban areas but mildly decrease from towns to cities in Europe when income is not controlled (figure 1). The categories contributing most to the result are housing energy and private transport, which cause high footprints and have a similar pattern as the total carbon footprint regarding the degree of urbanisation. In contrast, tangibles, services, other travel (public transport and holiday travel), and housing finance, construction and maintenance increase consistently with the increasing degree of urbanisation. The carbon footprint of food is generally lower in towns and cities than in rural areas. However, the consumption of restaurant services (included in the services category) is higher in towns and cities. The

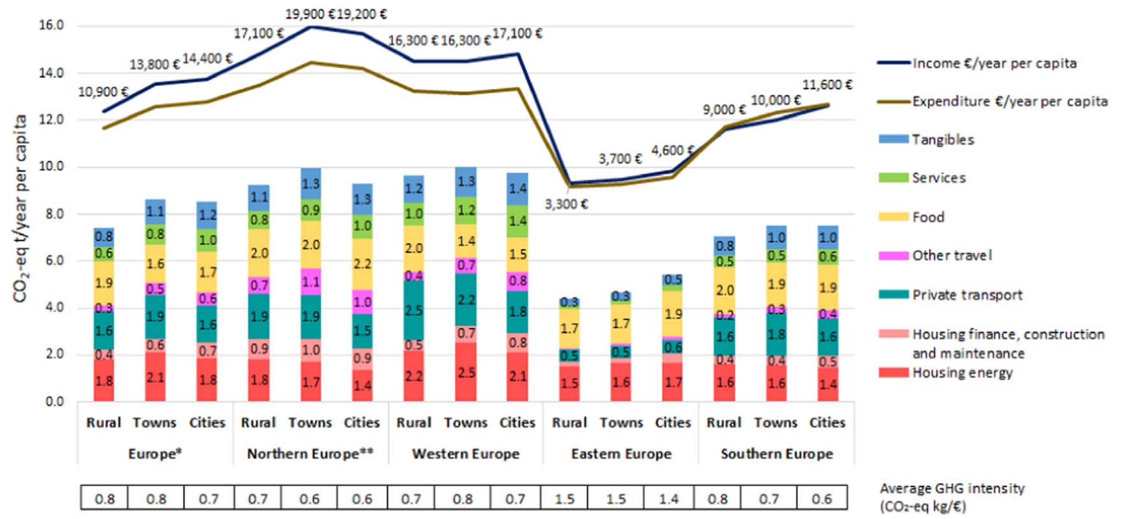

Figure 1. The average carbon footprint by the degree of urbanisation in Europe in 2010. *The EU28, excluding Austria, the Netherlands and Romania. **The GHG emissions of district heating in Denmark, Sweden and Finland are not fully included in the assessment (see the Methods section).

various degrees of urbanisation are characterized in supplementary table 21.

The total carbon footprint increases most clearly with the increasing degree of urbanisation in Eastern Europe. In Eastern Europe, the average income is lower than in the rest of Europe, and transformation from an agrarian society to an industrial society is still ongoing. Surprisingly, even the carbon footprint of private transport does not decrease with the increasing degree of urbanisation in Eastern and Southern Europe. In Northern and Western Europe, the carbon footprint of private transport is clearly lower in cities than in rural areas. In these wealthy parts of Europe, the infrastructure and affluence provide good commuting possibilities from rural to urban areas. Thus, the income of rural residents often comes from cities, whereas in less developed regions the income of rural residents is more dependent on local agriculture and industry.

The general patterns presented in figure 1 do not hold in all countries. The country-specific results are presented in supplementary figures 1–5 is available online at stacks.iop.org/ERL/14/114016/mmedia. For example, in Belgium, France and the UK, the carbon footprint decreases consistently with the increasing degree of urbanisation, even when income is not controlled. In these countries, the income level is actually lower in urban than in rural areas (supplementary table 18). Thus, the carbon footprint pattern is similar to what has been found in the US, where carbon footprints are highest in rich suburbs and lower in dense city cores, where lower income groups also reside (Jones and Kammen 2014, Underwood and Fremstad 2018). The carbon footprints increase most steeply with the increasing degree of urbanisation in Eastern European countries, such as Lithuania, Latvia, Hungary and Poland, but also in Cyprus and Luxembourg.

The impact of the degree of urbanisation on carbon footprints and income

When income, household size and age of children and adults are controlled, the carbon footprint decreases with the increasing degree of urbanisation in Europe (table 1, Model 1a). On average, the carbon footprint is 3% lower in towns and suburbs and 7% lower in cities than in rural areas. Similarly, Model 1b, which has expenditure instead of income as an explanatory variable, reveals that the GHG intensity of consumption is 5% lower in towns and suburbs and 12% lower in cities than in rural areas. The models with expenditure as an explanatory variable describe the GHG intensity, because they reveal how the emissions vary when expenditure is controlled (Shammin *et al* 2010).

Looking at the control variables, increasing household size decreases the carbon footprint when income is controlled (Model 1a) but increases the GHG intensity of consumption (Model 1b). Age has a statistically significant impact on the carbon footprint as well. Both young and seniors have lower carbon footprints than people of working age, and particularly small children in the household decrease the carbon footprint per person (Model 1a).

Income is on average 6% higher in cities than in rural areas, when the level of education, occupation and the age of the main income provider of household are controlled (supplementary table 6). This is likely to reflect the higher wage level and larger job markets in cities, but there may be additional reasons as well. High-income households may prefer cities as their residential location. There could be several reasons for that, for example better availability of goods and services, and better local and international transport connections. In addition, owner-occupants in cities can often trust that the value of their property is either steady or increasing, which is not always the case in

Table 1. The impact of the degree of urbanisation (deg. urb.) on carbon footprint per capita (CF) in Europe[a]. Income (Model 1a) and expenditure (Model 1b) as the main explanatory variable.

Dependent variable: ln (CF)	Model 1a			Model 1b		
Prob $> F = 0{,}000$ in all models	R^2=	0.55		R^2=	0.86	
	Coef.	Std. Err.	$P>\|t\|$	Coef.	Std. Err.	$P>\|t\|$
ln (disposable income per capita)	0.49	0.01	0.000	—	—	—
ln (expenditure per capita)	—	—	—	0.93	0.00	0.000
Household size: 1 person (ref.)	—	—	—	—	—	—
2 persons	−0.06	0.00	0.000	0.05	0.00	0.000
3 persons	−0.16	0.01	0.000	0.05	0.00	0.000
>3 persons	−0.24	0.01	0.000	0.06	0.00	0.000
Small children (<=4 y.)	−0.11	0.01	0.000	−0.05	0.00	0.000
School children (5–15 y.)	−0.05	0.01	0.000	−0.03	0.00	0.000
Young (16–24 y.)	−0.08	0.02	0.000	−0.13	0.01	0.000
Seniors (>=65 y.)	−0.05	0.01	0.000	−0.01	0.00	0.061
Deg. urb.: Rural areas (ref.)	—	—	—	—	—	—
Towns and suburbs	−0.03	0.01	0.000	−0.05	0.00	0.000
Cities	−0.08	0.00	0.000	−0.12	0.00	0.000
Country (categorical variable)		controlled			controlled	
Constant	4.71	0.08	0.000	0.43	0.02	0.000

[a] The EU28, excluding Austria, Italy, the Netherlands and Romania.

Table 2. The impact of the degree of urbanisation on the tested variables: increase or decrease (%) compared to rural areas and multiplier for odds compared to rural areas. The independent variables are the same as in Model 1a above: income per capita; household size; age of children and adults; and country, except for the last model, which predicts household income per capita when education, occupation, and age and gender of the main income provider are controlled.

	Towns and suburbs		Cities	
	Range between countries	Full model[a], country controlled	Range between countries	Full model[a], country controlled
Total CF per capita	−13…20%	−3%	−17…14%	−7%
CF Tangibles	0…38%	0%	−26…24%	5%
CF Services	−11…78%	5%	−12…95%	16%
CF Food	−16…18%	−4%	−15…20%	−5%
CF Private transport	−50%…0%	−10%	−45%…0%	−28%
CF Other travel	0…88%	20%	−31%…113%	35%
CF Housing finance, construction and maintenance	0%…98%	18%	0%…171%	36%
CF Housing energy	−19%…25%	−5%	−38%…52%	−13%
Odds that expenditure on private transport > 0	0.4…0.8	0.9	0.2…0.7	0.5
Odds that expenditure on holiday travel > 0	1…2.0	1.3	1…2.9	1.5
Expenditure when income is controlled	−11%…25%	2%	−9%…23%	5%
Income when education and occupation are controlled	−6%…12%	1%	−16%…53%	6%

[a] The EU28, excluding Austria, Italy, the Netherlands and Romania.

more remote locations. However, this is also likely to increase the differences in affluence between urban and rural residents over time. It should be noted that the income pattern is not uniform. As mentioned above, in Belgium, France and the UK, the income level is lower in urban than in rural areas.

Expenditure is also on average 5% higher in cities than in rural areas, when income is controlled (supplementary table 5). This means that city residents spend a larger share of their income. This may reflect more consumption-centred lifestyles in cities (Heinonen *et al* 2013), higher living costs, or trust in personal economy in the future. As discussed above, cities provide generally higher salaries, and better job opportunities and education possibilities than in rural areas.

The impact of the degree of urbanisation on the carbon footprint varies by country (table 2 below and supplementary table 7). An increasing degree of urbanisation decreases carbon footprints in 14 countries when income is controlled: Belgium, Bulgaria, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Hungary, Portugal, Finland, Sweden and the UK. The results of Finland and Sweden, in particular, suffer from bias related to the exclusion of emissions caused by the heating of apartment buildings due to data limitations (see the Methods section for details). In Denmark and Malta, the impact of urbanisation is statistically insignificant, whereas in 8 countries there are opposite effects, so that carbon footprints increase with the increasing degree of urbanisation when income is controlled: Czech Republic, Cyprus, Latvia, Lithuania, Luxembourg, Poland, Slovenia and Slovakia. In addition, in the majority of European countries, the degree of urbanisation increases expenditure when income is controlled, and increases income when the level of education, occupation and the age of the main income provider of household are controlled (table 2 below and supplementary tables 17 and 18).

The impact of the degree of urbanisation on specific consumption categories

While the impact of the degree of urbanisation on total carbon footprint is modest in the majority of European countries, the impact on some specific groups of commodities is clearer (summary of the results in table 2 below, the full models in supplementary tables 1–4). However, as table 2 illustrates, the results are not uniform between countries, but the range of the impact is wide for most commodity categories (country-specific results in supplementary tables 8–16). On average the carbon footprint of private transport and housing energy decrease clearly and strongly with the increasing degree of urbanisation. At the same time, the carbon footprint of finance, construction and maintenance of housing, other travel (public transport and holiday travel) and services increase. The sector of housing finance and construction illustrates the pressure on housing prices and new residential construction in urban areas. Although the rentals and imputed rentals do not necessarily reflect very well the GHG emissions of construction at the household level, they do reflect the concentration of new construction in urban areas. It should be noted that the GHG intensity of the sector is very low (0.2 CO_2-eq kg/€, supplementary table 20) and does not include household energy consumption. Thus, the impact of the sector on the total carbon footprint is low.

For private transport and holiday travel, there is a significant amount of households who have no expenditure on these consumption categories (supplementary table 21). This is not captured by the general regression model, which only reveals the impact on the amount of travel among those who drive or make holiday trips (see the Methods section for details). Thus, table 2 presents the impact of the degree of urbanisation on the likelihood of driving, P(expenditure on private transport > 0), and holiday travel, P(expenditure on holiday travel > 0), as well. The multiplier for odds compared to rural areas is less than one if the likelihood decreases, and above one if the likelihood increases. The odds depend on the other variables in the model as well, such as household size and income (supplementary table 4). As table 2 reveals, the likelihood of driving decreases and the likelihood of holiday travel increases with the increasing degree of urbanisation. This is line with the results of the general regression model, and thus strengthens the found patterns.

Comparison of carbon footprints between the EU and other countries

As mentioned above, carbon footprints do not follow the degree of urbanisation similarly in all EU countries. For example, in Germany they increase modestly, whereas in France they decrease with an increasing degree of urbanisation (figure 2). In the US, the income level and carbon footprints tend to be highest in suburban settings, whereas the residents of dense urban areas have the lowest carbon footprints (Underwood and Fremstad 2018). In California, however, the pattern and scale of the carbon footprints are more similar to the European average (Heinonen 2016). In China, carbon footprints increase steeply with increasing level of urbanisation (Wiedenhofer *et al* 2017). The carbon footprints are overall much lower than in the US and Europe, but the wealthiest urban residents in China have carbon footprints that are comparable in size to the European carbon footprints. It should be noted that government consumption and gross fixed capital formation are excluded from all the carbon footprints in figure 2. These are likely to be higher in Europe and China than in the US.

Discussion and conclusions

Summary of the results

The purpose of this study was to provide a comprehensive and coherent view of the household carbon footprint patterns in urbanising Europe. Previous studies on the relationship between the level of urbanisation and consumption-based carbon footprints have focused on individual countries and cities, and the results from developed countries have been somewhat contradictory (Ottelin *et al* 2019). Thus, we provide a comparable analysis on 25 EU countries to clarify the issue. We found that the patterns of household carbon footprints vary from country to country. In particular, we found that there is a significant difference between the economically less developed Eastern Europe and the rest of Europe. In Eastern Europe, carbon footprints have a similar pattern as in developing countries: they increase clearly with the increasing degree of urbanisation. By contrast, in some Western European countries, such as France and Belgium, carbon footprints clearly decrease with the increasing degree of urbanisation, even when income is controlled. Overall in the studied countries, carbon

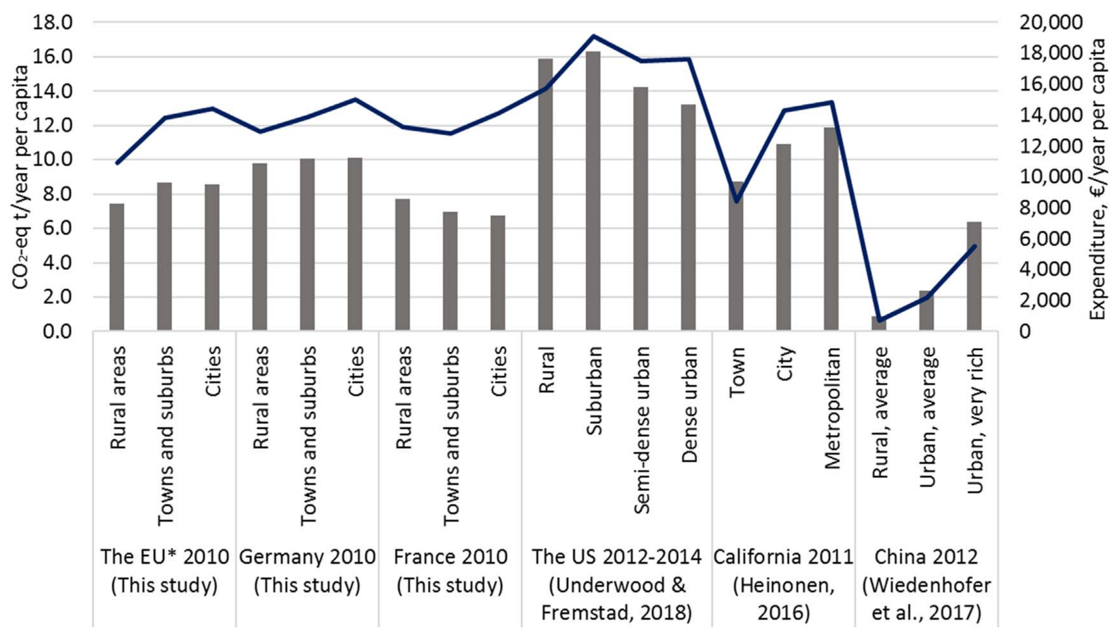

Figure 2. Average carbon footprint of household consumption by level of urbanisation in the EU and selected reference countries. *The EU28, excluding Austria, the Netherlands and Romania.

footprints are 7% lower in cities than in rural areas when income and household characteristics are controlled. However, this is compensated by the 6% higher average income in cities. Similar results have been presented before for individual countries (Minx *et al* 2013, Nässén *et al* 2015, Ottelin *et al* 2015, Gill and Moeller 2018).

Limitations of the study

The main sources of uncertainties relate to the used Eora26 MRIO model and Eurostat HBS. The Eora26 is an aggregate model that includes only 26 economic sectors. For example, there is only one sector for food, which means that our carbon footprint model does not separate between vegetarian and animal-based products. In addition, the Eora26 does not match directly to the COICOP categories of the HBS. Thus, the GHG intensities (CO2-eq kg/€) of different COICOP categories used in the study (see supplementary table 20) should be considered as approximations. However, the intensities calculated with the Eora26 are well in line with more detailed models. They are low for services, intermediate for manufactured products, and high for GHG-intensive products, such as food. The GHG intensities of energy, motor fuels and air travel are more accurate than the intensities of other consumption categories in our study, since they are mainly determined by the combustion-phase emissions, which we added into the model based on several data sources (see the Method section for details). Housing energy and motor fuels are the two categories that contribute the most to the carbon footprints.

It should be noted, that while the carbon footprints for EU on average are well in line with previous studies, the results for small individual countries should be interpreted with more caution. This is because Eora26 has been balanced to create a consistent global model of 187 countries. In theory, the national accounts of different economies should match. The exports from country A to country B in country A's account should show as imports from country A to country B in country B's account. In practice, the numbers do not always match, and thus the MRIO developers have to make adjustments into the models. In addition, the economic sectors used in the accounts do not always match. Because of these inconsistencies in the original data, the results of small countries may in some cases become distorted during the balancing process (Eora FAQ: http://worldmrio.com/documentation/faq.jsp).

The Eurostat HBS has limitations as well. Although there are continuous attempts to harmonise the surveys between the EU member states, there are still differences in data collection and processing (Eurostat 2018c), that lead to differences in data quality. Thus, we restrain from comparing the sizes of carbon footprints between countries, and only examine the urban-rural variation of carbon footprints within countries. Within countries, the survey method is the same in rural and urban areas, which allows making the comparisons.

Suggestions for future research

While the impacts of urbanisation on consumption-based carbon footprints has interested many researchers, there are still open questions. Essentially, urbanisation is a dynamic process. Cross-sectional analyses are vulnerable to a self-selection bias. Comparing households living in rural and urban areas is not the same as studying the changes related to rural-urban migration. The groups are self-selected and the observed differences in carbon footprints may be caused by omitted variables, such as personalities and attitudes (Ottelin 2016). Longitudinal datasets would provide a more rigorous basis for studying causal relationships, but longitudinal expenditure surveys are scarce. Zhang *et al* (2016) suggest a model combining propensity score matching and regression analysis, which is a step forward.

Our study revealed also that analyses of individual countries are still needed. While comparable studies of several countries are important, they are limited in their level of details. The HBSs of some individual countries actually include important variables that are missing from the combined dataset, such as living space (m^2), construction year of the building, and information about car-ownership (see e.g. Ottelin *et al* 2015). Thus, data provided by individual countries may allow studying research questions that cannot be answered with the more generalized data.

An important issue that remains unanswered is how to allocate the government consumption and investments for individual households in order to include these emissions in household-level carbon footprint models. Public welfare services, such as education and health care, can be allocated for the households who use them, if appropriate data is available (Ottelin *et al* 2018a). However, the question of infrastructure, such as transportation, energy and water networks, is more difficult to address.

Policy implications

The EU is in many ways at the forefront of global climate action, and it had an important role in promoting Kyoto protocol and shaping the Paris Agreement. The ambitious targets of the EU are to cut 20% of GHG emissions by 2020, 40% by 2030 and 80%–95% by 2050 compared to 1990 levels. The main policy tools include the EU emissions trading system (ETS), national targets, the renewable energy directive, energy efficiency directives, and research and innovation financing. As a recent study by Le Quéré and colleagues reveal, energy efficiency and renewable energy policies have particularly been successful (Le Quéré *et al* 2019). However, the global GHG emissions have not yet turned down (IPCC (2018)).

Similarly to its predecessors the Kyoto Protocol and The United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement is based on territorial emission accounting, as are the climate targets of the EU. Territorial accounting allocates emissions to the country of origin and lacks insights into the emissions embodied in trade and transboundary flows (Ramaswami *et al* 2012, Ramaswami *et al* 2016, Wiedmann 2016). Particularly in developed countries, where a significant share of the carbon footprint is composed of these embodied emissions imported from other countries, it would be relevant to use consumption-based accounting (CBA) and targets as a complementary policy tool with the territorial accounting (Dolter and Victor 2016, Chen *et al* 2017, Clarke *et al* 2017, Steininger *et al* 2018, Ottelin *et al* 2019). Although it is more difficult for the EU to affect emissions embodied in imported goods than direct emissions inside EU borders, it could be a more cost-effective mitigation strategy, which has been previously argued for at the city level (Mi *et al* 2016, Chen *et al* 2017, Millward-Hopkins *et al* 2017). Furthermore, it would enable the EU to take more responsibility of global emissions. As argued by Hubacek and colleagues, the global poverty reduction goals are possible to achieve in a carbon constrained world, if rich countries and regions take more responsibility over the decarbonisation of production and consumption (Hubacek *et al* 2017).

CBA is often misunderstood by policymakers as a method that highlights the consumers' responsibility for GHG emissions. Actually, CBA reveals how difficult it is for ordinary consumers to make consistently responsible consumption choices. Studies based on CBA have revealed how consumer actions often rebound or even backfire (Nässén and Holmberg 2009, Druckman *et al* 2011, Chitnis *et al* 2013, Ottelin 2016). One of the main assets of CBA is that it captures these rebound effects and at the macro-economic scale as well (see the review by (Turner 2013), and even if the induced emissions locate to another country or region. If territorial accounting was complemented with CBA, policymakers would have more information on the possible and actual rebound effects of climate policies, which could potentially increase the efficiency of climate strategies significantly (Wiedmann *et al* 2016, Ottelin *et al* 2018a). Of course, if all countries in the world were committed to reduce their territorial emissions and had the capacity to act accordingly, CBA might not be needed. However, this is not the case. Developing countries have a limited capacity to act (Steininger *et al* 2014), and some countries, the US most notably, have not even signed the Paris Agreement. This may jeopardize the climate actions of the EU as well. For example, it is possible that some low carbon investments in the EU require imported products from other countries. Without CBA, the embodied emissions within these imports remain unaccounted.

From the perspective of urbanisation, the emission accounting method is particularly important, which is highlighted in the result of this study. The findings reveal that the carbon footprint caused by private transport, housing energy and food (not including restaurant services) decreases with the increasing degree of urbanisation. A large share of these emissions is included in territorial accounting. At the same time, the carbon footprint caused by other travel (public transport and holiday travel), services, and housing finance, construction and maintenance increase.

Aside from the first category, these consumption categories consist mainly of embodied emissions, of which a large share is imported and thus not included in the current GHG accounting of the EU regions. Furthermore, international travel is also excluded from the territorial accounting. Several previous studies have revealed that long-distance travel tends to increase with an increasing level of urbanisation (see the review by Czepkiewicz *et al* 2018). The above issues may lead to an illusion that urbanisation as such helps to achieve the climate targets of the EU, while the impact on global emissions is likely to be small or even negligible. Similar illusions are also possible for other climate policies when reporting is based solely on territorial accounting.

Thus, like several other authors (Feng *et al* 2014, Chen *et al* 2016, Dolter and Victor 2016), we call for complementing current territorial accounting with official CBA and consumption-based climate strategies and targets. CBA can be applied to other environmental aspects as well, which would support transition to an economy that is compatible with planetary boundaries (Galli *et al* 2013, Meyer and Newman 2018). It is also possible for individual cities to implement CBA. For example, the C40 Cities Climate Leadership Group has recently assessed the consumption-based carbon footprints for 79 of its member cities, including many important European cities, such as London, Paris, Stockholm and many others (C40 Cities 2018). In addition, for example the city of Gothenburg has already implemented consumption-based targets in their climate programme (City of Gothenburg 2014). Of course, implementing CBA alone is not enough to cut the emissions. The application of CBA often leads to the call for more stringent carbon pricing policies, including carbon taxes, ETS and carbon tariffs (Ottelin *et al* 2019). It has recently been illustrated and tested in practice how carbon trading can also take place between cities (Chen *et al* 2016, Mi *et al* 2016). The essence from the CBA perspective is that the revenues of carbon pricing should be used for decarbonising the production of goods and services globally, not just within a city's or country's territory (Steininger *et al* 2014, Afionis *et al* 2017, Shan *et al* 2018). In other words, the EU should not stop importing GHG intensive products from developing countries, because this would jeopardize economic and social development goals. A better option may be to use carbon pricing mechanisms (covering imports) to collect funds that could be invested into the decarbonisation of GHG intensive industries in developing countries, for example through knowledge and technology sharing.

At the EU level, increasing urbanisation is particularly addressed by the European Commission's Urban Agenda for the EU (EC 2016), which aims for liveable and innovative cities and promotes cooperation and knowledge sharing between the EU Member States and cities. Unfortunately, climate action is not in the list of the priority themes of the Agenda. Although climate actions are included in some of the themes (circular economy, energy transition, urban mobility), the lack of an overarching theme may lead to the fragmentation of climate strategies and sub-optimisation instead of dealing holistically with global GHG emissions. However, while waiting for stronger carbon pricing policies, which may take time to develop, it should be recognised that different areas have different strengths regarding climate change mitigation. The results of this and previous carbon footprint studies highlight, that in rural and suburban areas the focus should be on technological solutions to decrease the emissions caused by housing energy consumption and private transport (Ottelin *et al* 2015). Arranging public transportation for these areas would be difficult and expensive. By contrast, cities benefit from the economies-of-scale and proximity of households and services, which provides a fruitful soil for public transport and sharing economy (Fremstad *et al* 2018). Cities would also benefit from improving long-distance railway connections, which could reduce air travel and the related emissions.

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