Carbon footprints of cities and other human settlements in the UK

Jan Minx[1], Giovanni Baiocchi[2,3], Thomas Wiedmann[4,5], John Barrett[6], Felix Creutzig[7,8], Kuishuang Feng[3], Michael Förster[9], Peter-Paul Pichler[1], Helga Weisz[1] and Klaus Hubacek[3]

[1] Potsdam Institute for Climate Impact Research, Potsdam, Germany
[2] Norwich Business School, University of East Anglia, UK
[3] Department of Geographical Sciences, University of Maryland, USA
[4] School of Civil and Environmental Engineering, University of New South Wales, Australia
[5] ISA, School of Physics A28, The University of Sydney, Australia
[6] School of Earth and Environment, University of Leeds, UK
[7] Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany
[8] Department for the Economics of Climate Change, Technische Universität, Berlin, Germany
[9] Geoinformation in Environmental Planning Lab, Technische Universität Berlin, Germany

E-mail: jan.minx@pik-potsdam.de

Abstract

A growing body of literature discusses the CO_2 emissions of cities. Still, little is known about emission patterns across density gradients from remote rural places to highly urbanized areas, the drivers behind those emission patterns and the global emissions triggered by consumption in human settlements—referred to here as the carbon footprint. In this letter we use a hybrid method for estimating the carbon footprints of cities and other human settlements in the UK explicitly linking global supply chains to local consumption activities and associated lifestyles. This analysis comprises all areas in the UK, whether rural or urban. We compare our consumption-based results with extended territorial CO_2 emission estimates and analyse the driving forces that determine the carbon footprint of human settlements in the UK. Our results show that 90% of the human settlements in the UK are net importers of CO_2 emissions. Consumption-based CO_2 emissions are much more homogeneous than extended territorial emissions. Both the highest and lowest carbon footprints can be found in urban areas, but the carbon footprint is consistently higher relative to extended territorial CO_2 emissions in urban as opposed to rural settlement types. The impact of high or low density living remains limited; instead, carbon footprints can be comparatively high or low across density gradients depending on the location-specific socio-demographic, infrastructural and geographic characteristics of the area under consideration. We show that the carbon footprint of cities and other human settlements in the UK is mainly determined by socio-economic rather than geographic and infrastructural drivers at the spatial aggregation of our analysis. It increases with growing income, education and car ownership as well as decreasing household size. Income is not more important than most other socio-economic determinants of the carbon footprint. Possibly, the relationship between lifestyles and infrastructure only impacts carbon footprints significantly at higher spatial granularity.

Keywords: carbon footprint, cities, human settlements, local consumption, emission drivers

S Online supplementary data available from stacks.iop.org/ERL/8/035039/mmedia

1. Introduction

Human settlements—and in particular cities—are the hotspots of human activities and main drivers of greenhouse gas (GHG) emissions. Based on a growing recognition of a potentially important role of local action in climate change mitigation, a mounting body of scientific literature is focusing on understanding GHG emissions attributable to cities and other human settlements. While some important, general insights can be derived from this body of work, recent assessments of the existing scientific evidence on human settlements point towards a series of challenges (UN-HABITAT 2011, GEA 2012).

One major challenge is the availability of comprehensive, consistent and transparently documented data on human settlements. Important dimensions of this challenge are multiple ways of defining the boundaries of human settlements (Fons-Esteve *et al* 2008, Weisz and Steinberger 2012), the diversity of accounting approaches (Kennedy *et al* 2010) and the lack of regularly organized data collection efforts (GEA 2012) even though the latter situation is currently improving with a series of new data collection initiatives (e.g. Covenant of Mayors 2010, C40, ICLEI *et al* 2012).

A large part of the recent discussion has focused on the question of how to appropriately account for emissions at the urban scale (Ramaswami *et al* 2008, Kennedy *et al* 2009, Hillman and Ramaswami 2010, Kennedy *et al* 2010, Chavez and Ramaswami 2011, Kennedy *et al* 2011, Kennedy and Sgouridis 2011, Minx *et al* 2011, Ramaswami *et al* 2011, Baynes and Wiedmann 2012, Ramaswami *et al* 2012, Chavez and Ramaswami 2013). Territorial emission accounts report all GHG emissions directly released from sources within the settlement territory. Recent assessments have highlighted the need to complement territorial emissions accounting by approaches that include 'upstream' or 'embodied' emissions (e.g. GEA 2012). The concept of the carbon footprint (CF) (Wiedmann and Minx 2008) has been used by many as an umbrella term for such approaches (Druckman and Jackson 2009, Larsen and Hertwich 2009, Minx *et al* 2009, Larsen and Hertwich 2010a, 2010b, Lenzen and Peters 2010, White *et al* 2010, Heinonen and Junnila 2011a, 2011b, Heinonen *et al* 2011, Jones and Kammen 2011, Petsch *et al* 2011, Wright *et al* 2011, Chavez and Ramaswami 2013, Paloheimo and Salmi 2013). In this letter we apply a consumption-based definition of the CF. It includes all GHG emissions released in the global supply chain during the production of final goods and services consumed on the territory of a human settlement within a given year. Other CF concepts with different system boundaries exist. For example, the community-wide infrastructure CF includes all territorial GHGs as well as embodied GHG emissions associated with all trans-boundary infrastructure supply chains (Ramaswami *et al* 2008, Hillman and Ramaswami 2010, Chavez and Ramaswami 2011, Ramaswami *et al* 2011, Chavez *et al* 2012, Ramaswami *et al* 2012, Chavez and Ramaswami 2013, Lin *et al* 2013a, 2013b). Such trans-boundary footprints combining territorial and embodied GHG emissions are further discussed in the supplementary information (SI, available at stacks.iop.org/ERL/8/035039/mmedia).

The empirical evidence on GHG emissions of human settlements is still very limited and major gaps are prevailing. First, available studies mainly focus on cities and urban areas. Much less is known about emissions in rural areas to contextualize findings related to urban areas and differences in emissions across density gradients. Second, despite growing attention, evidence on CFs of cities and other human settlements as well as evidence from trans-boundary approaches remains scarce (GEA 2012). Therefore little is known about the global GHG emissions of rural and urban living considering the supply chains emissions in the global hinterland of human settlements. Third, due to a lack of sufficiently large standardized and consistent datasets, studies with small sample size dominate the literature, focusing on a descriptive analysis of emission inventories, and preventing more in-depth statistical analysis of the determinants of urban GHG emissions. In particular, a comprehensive driver analysis is missing for trans-boundary and CF accounts across density gradients. Finally, consistent comparisons between territorial and CF accounts are largely absent in the published literature (GEA 2012).

In this letter we construct a comprehensive set of CF estimates for the UK at the local level, comprising all rural and urban areas. We focus our estimations on the energy and process-related CO_2 emission component of the CF, i.e. our calculations do not include CO_2 emissions from land-use change and non-CO_2 GHG emissions. Our methodology directly links the production of goods and services across global supply chains to local consumption activities. We compare CF results with extended territorial CO_2 emission estimates for 434 municipalities in the UK and discuss their relationship. Municipalities are grouped into density classes and interpreted as representations of different types of human settlements. Based on a non-parametric statistical analysis we identify socio-economic, infrastructural and geographic determinants that drive local CFs in the UK. Key questions we pose are: how does the CF of human settlements in the UK compare to the settlement's territorial emissions? What determines the size of the CFs of human settlements in the UK? Are CFs mainly determined by income and socio-economic characteristics of an area or its physical make-up?

After introducing the methodology in section 2 we present the results including an analysis of drivers of local CFs. We conclude with a discussion of our results in the context of the relevant scientific and policy-related literature. The SI contains a more comprehensive literature review, all required methodological details and some additional results. The dataset used for the statistical analysis can be downloaded from the journal website.

2. A hybrid modelling approach for estimating the global carbon flows from local consumption activities

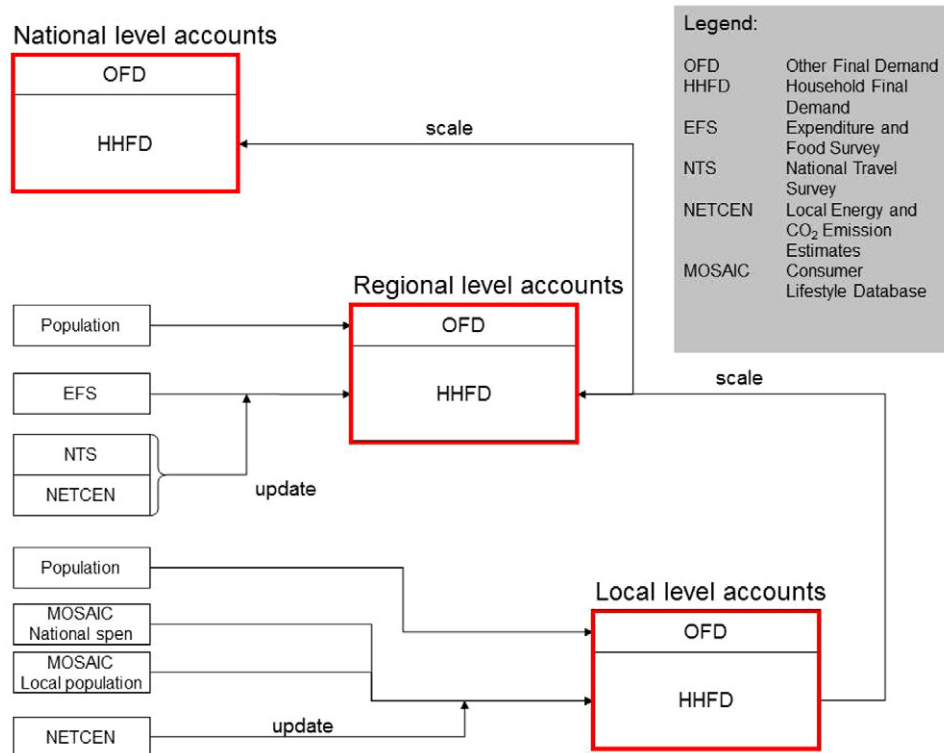We estimate the CF of the 434 muncipalities in the UK. We use a classification by the Office for National

Figure 1. Overview of methodology for estimating detailed local final demand matrices for municipalities in the UK.

Statistics that groups these local areas into five categories of human settlement types ranging from 'Major Urban' to 'Rural 80' (see the SI). For estimating the global carbon flows of consumption activities in municipalities across the UK, we combine information on global production from a global multi-regional input–output model with local geo-demographic consumer lifestyle information. The term 'geo-demographic' is defined broadly as 'analysis of people by where they live' (Harris *et al* 2005). This can be seen as an attempt to classify areas and their associated lifestyles in terms of collective consumption and locational proximity including geographic, infrastructural as well as socio-demographic factors that characterize them (Harris *et al* 2005, Longley 2012). As geo-demographics are already defined by spatial and consumption factors, a geo-demographic concept is more adequate to be applied to CF analysis of human settlements (cf Druckman *et al* 2008, Druckman and Jackson 2009, Minx *et al* 2009) than conventional lifestyle definitions often used by Statistical Bureaus (Duchin 1998, Duchin and Hubacek 2003, Minx *et al* 2009, Baiocchi and Minx *et al* 2010).

Details of the environmentally extended multi-regional input–output model for the UK have been described elsewhere (Baiocchi and Minx 2010, Wiedmann *et al* 2010). A general outline of the model structure and calculus can be found in the SI. Essentially, the model distinguishes 178 economic sectors across the UK and three world regions. Detailed trade activities between the UK and the other three regions are represented, but not trade between the three non-UK regions (cf Andrew *et al* 2009). The multi-regional input–output model allows the allocation of CO_2 emissions to UK final consumption of goods and services regardless of where

they have been emitted in the global supply chain during production. However, as the underlying input–output data only give information at the national level, it is essential in the estimation of local CFs to devise a methodology for estimating final consumption at the local level. Note that the proposed methodology could be applied for more spatially detailed analysis.

We use a hierarchical three-step (local, regional and national level) hybrid methodology for estimating final consumption in local authority areas across the UK. A conceptual overview of this methodology is provided in figure 1. This hierarchical approach integrates data from multiple sources and prioritizes the most robust information. The hierarchy acknowledges that spatially more aggregated data tend to have less uncertainty attached. Our methodology also prefers physical over monetary data, as far as possible, to avoid quantity estimates being biased by inhomogeneous or volatile prices (Weisz and Duchin 2006).

We use geo-demographic information from the MOSAIC dataset to estimate local household consumption spending for all 434 municipality areas in the UK. MOSAIC is a consumer classification system with detailed expenditure, socio-economic and geo-demographic data (Experian 2004). For methodological aspects see Harris *et al* (2005). The MOSAIC database distinguishes consumer spending of 61 lifestyle types and 11 lifestyle groups (for more information, see the SI) across 48 consumption categories at the national level. The database also contains information about the spatial distribution of these lifestyle types across municipalities. Combining these two pieces of information we derive initial estimates of local consumer spending. Estimates are based

on the assumption of homogeneous consumer preferences within each lifestyle type across space. In order to address this limitation, we update these initial estimates using more reliable and more detailed local and regional data sources wherever possible. At the local level we update household spending on domestic energy consumption with data measured in energy units (kWh) and further adjust local consumer expenditure matrices by matching them with regional spending estimates derived from the expenditure survey across all consumption activities. Accordingly, we match the sum of all regional matrices with national level data.

Household consumption contributes 70% of the UK's CF (Minx *et al* 2009). The remainder is attributable to government services and capital investments. We downscale the national accounts for those to the local level on an equal per capita basis. This means we assume that every citizen in the UK enjoys the benefits from government expenditures and capital investments in the same way. This is a strong assumption. Future research could attempt addressing this issue by endogenising government consumption and capital investment (Lenzen and Treloar 2005, Miller and Blair 2009). Researchers have also downscaled government spending based on local government expenditure statistics, but such information is not available for the UK (Larsen and Hertwich 2010a, 2010b). Overall, the proposed approach goes beyond mere geo-demographics and adjusts consumption patterns according to local conditions. This is essential for analysing local CF results.

CF estimates are calculated for the year 2004. We compare our CF estimates with extended territorial CO_2 emission accounts for this year. We take these estimates from the 2004 edition of the Local Authority Carbon Dioxide Emissions published by the UK Department for Environment, Food and Rural Affairs and AEA Technologies (DEFRA and AEA Teachnologies 2006). Note that more recent editions of this data are published by the Department for Energy and Climate Change (DECC).[10] In general, these emission accounts report scope 1 and 2 emissions (cf WBCSD and WRI 2004). Scope 1 emissions are the territorial CO_2 emissions from sources within the geopolitical boundaries of the municipality. Scope 2 emissions are emissions associated with electricity production but allocated to the municipality were the electricity is consumed and not where it is produced.

We use general additive models (GAMs) to analyse the drivers determining local CFs in the UK. GAMs are useful when we have no *a priori* reason to choose a specific functional relationship between GHG emissions and other determinants. It is a generalization of the standard OLS regression, as it allows for a flexible and easily interpretable nonlinear relationship between dependent and each independent variable, whilst remaining computationally tractable. Our model includes variables such as income per capita, household size, per capita car ownership, and proportion of highly educated people. Details on the model and methodology used are available in the SI. Data for the

analysis are taken from the neighbourhood statistics provided by the Office for National Statistics[11], which largely consists of census information. Heating degree days (HDD) have been calculated by overlaying the GIS data for the local authority layer with the 5 km gridded HDD data for 2005 available from the Met Office UKCIP dataset (Met Office 2011). A more detailed data description can also be found in the SI.

3. Results

Figure 2 shows the per capita CF across all 434 municipalities in the UK. It ranges from 10.21 (Newham) to 15.51 (City of London) tonnes of CO_2 emissions (tCO_2). This compares to an average UK CF of 12.5 tCO_2 emissions. There is no obvious regional pattern emerging. London contains the areas with both the lowest and highest CF in the UK. The majority of areas in London have a below average CF. Areas close to the borders of Greater London tend to have a comparatively high CF, but there is no consistent impact of the distance to the centre. The apparent outward increase in emissions is largely explained by the income distribution ($R^2 = 0.49$) in these local authorities. Note that for extended territorial emissions there is a clear correlation between emissions and the distance to the city centre. Per capita CO_2 emissions are low close to the centre (with the noted exception of the City of London itself) then systematically increase peaking between 20 and 30 km distance and then decreasing again (see the SI).

The CF of local areas tends to be higher than extended territorial CO_2 emissions. This is shown in figure 3, where roughly 90% of the data points stay below the 45° line. This is not surprising as the UK is a net importer of CO_2 emissions (Minx *et al* 2009, Baiocchi and Minx 2010, Wiedmann *et al* 2010, Peters *et al* 2011, Sinden *et al* 2011). The figure shows that this pattern is consistently more pronounced for urban than for rural areas, i.e. for any given CF level extended territorial CO_2 emissions tend to be lower for urban areas. There are industrialized areas with much higher extended territorial CO_2 emissions than CFs, which produce and export carbon intensive goods to other parts of the UK and abroad. Figure 3 highlights that these areas tend to be located in rural areas, but there are also production-oriented urban areas following such a pattern.

Per capita CFs are more homogeneous across municipalities than the corresponding extended territorial CO_2 emissions. This is shown in figure 3. CF estimates all fall into a narrow band between 10 and 15 tCO_2/cap. Ranges for extended territorial estimates among municipalities are much larger, starting from 4.3 tCO_2/cap and extending up to 60 tCO_2/cap—in one case even to 160 tCO_2/cap. Nevertheless 97% of all municipalities have extended territorial emissions below 20 tCO_2/cap.[12]

---

[10] www.gov.uk/government/organisations/department-of-energy-climate-change/series/sub-national-greenhouse-gas-emissions-statistics.

[11] www.neighbourhood.statistics.gov.uk/dissemination/.

[12] Part of the variation is determined by choosing per capita CO_2 emissions as comparative metric. The mix of land-uses between commercial and residential activities and the associated infrastructure will influence the territorial per capita emission estimates. However, we show in the SI (available at stacks.iop.org/ERL/8/035039/mmedia) that the higher variation in CO_2 emissions also holds without normalization except for some extreme cases like the 'City of London'.

Carbon Footprint

t CO$_2$ / capita

- 10.21 - 11.96
- 11.97 - 12.40
- 12,41 - 12.88
- 12.89 - 13.35
- 13.36 - 15.51

London Area
(<= 50 km)

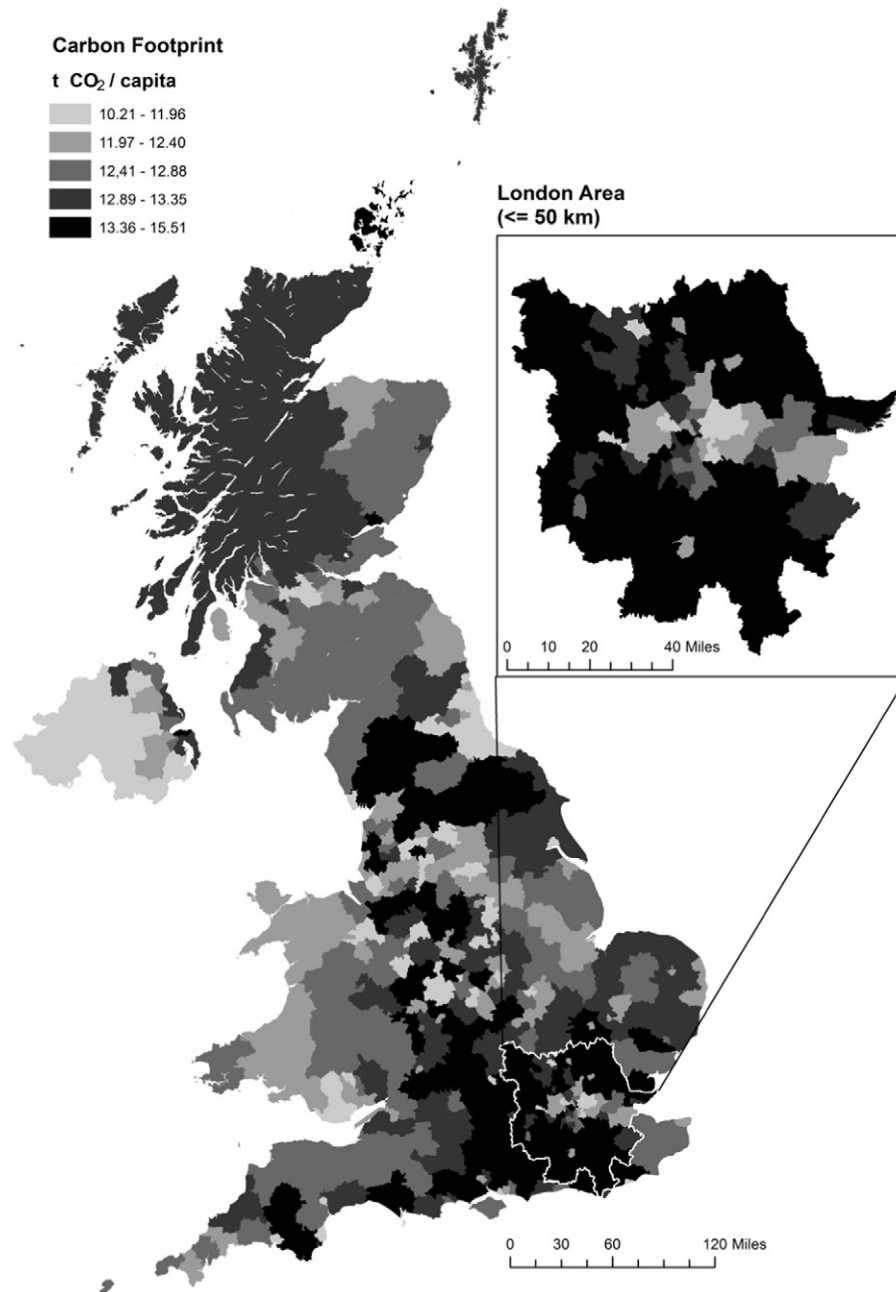0   10   20   40 Miles

0   30   60   120 Miles

Figure 2. Per capita CF of 434 municipalities in the UK. Inset shows London and municipalities that border within 50 km radius from centre. There is no clear pattern in terms of the geographic positioning of high and low CF municipalities. Only around London is a ring of municipalities with a high CF, while municipalities within Greater London tend to have a below average CF.

The 'City of London' has the highest per capita territorial CO$_2$ emissions as well as the highest per capita CF, but at the same time exhibits comparatively low total CO$_2$ emissions of both types. The simple reason is that this is a business district with a very small, but rich residential population (see also footnote 12). There are twelve other local areas with extended territorial CO$_2$ emissions between 20 and 60 tCO$_2$ per capita. These areas typically have high overall emissions and tend to be located in the North of England, where there are still some larger industrial facilities like in Redcar and Cleveland (55 tCO$_2$/cap), Wansbeck (56 tCO$_2$/cap) or North Lincolnshire (57 tCO$_2$/cap).

Figure 4 shows extended territorial CO$_2$ emissions and CFs across different human settlement types as defined by the Office for National Statistics. Error bars show variation between the 25th and 75th percentile. Moving along the *x*-axis from the left to the right, human settlement types become increasingly rural from 'Major Urban' to 'Rural 80' (see the SI). The left panel in figure 4 shows that extended territorial CO$_2$ emissions increase as we move from highly urban (6.7 tCO$_2$/cap) to highly rural (10.0 tCO$_2$/cap) human settlement types. For the CF—as shown in the right panel—our results indicate that on average the CF of urban areas is lower than of rural areas, but that there are little differences among rural
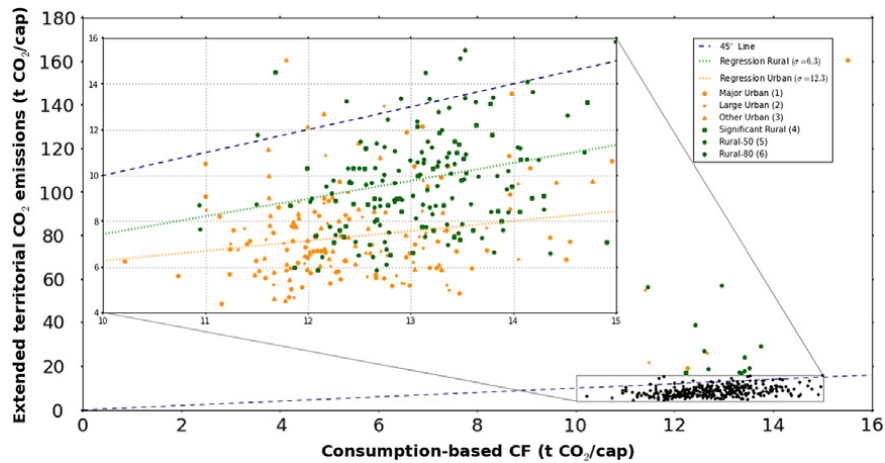
Figure 3. Extended territorial (scope 1 and 2) per capita CO_2 emissions and per capita CFs across 354 municipalities in England. Rural (green) and urban (yellow) settlement types are distinguished. Robust regression lines for the two subsamples are also shown. The graph shows that per capita CFs are larger than extended territorial per capita CO_2 emissions for most municipalities represented by all data points to the right of the diagonal (dashed) line. The regression lines show that this is pattern is more evident for urban municipalities. The 95% confidence interval for urban, as opposed to rural, does not include 1 (45° line). Also, the error of regression for urban is twice as large as for the rural subsample, indicating a much more consistent behaviour for rural municipalities. Inset enlarges for the following range: *x*-axis 10–15 tCO_2/cap, *y*-axis 4–16 tCO_2/cap.
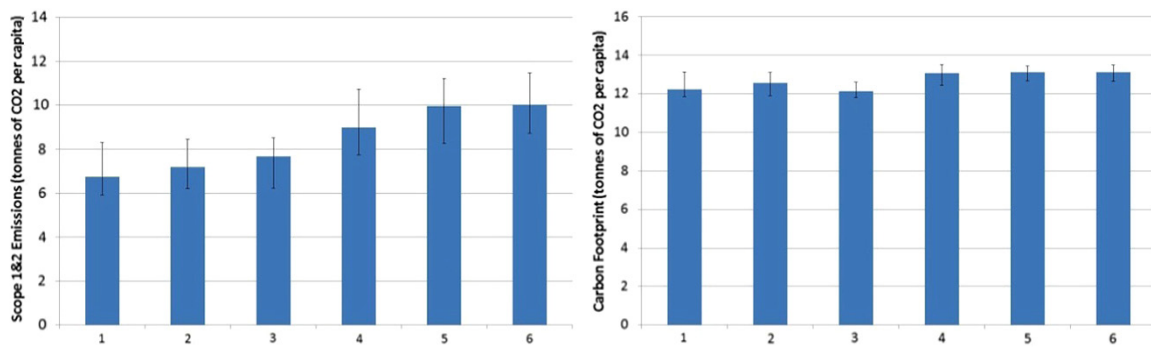

Figure 4. Extended territorial (scope 1 and 2) per capita CO_2 emissions and per capita CF by human settlement types in England: 1—major urban ($N = 76$); 2—large urban ($N = 45$); 3—other urban ($N = 55$); 4—significant rural ($N = 53$); 5—rural 50 ($N = 52$); 6—rural 80 ($N = 73$). Further definitions are provided in the supplementary information (available at stacks.iop.org/ERL/8/035039/mmedia). The figure shows that there is a clear positive relationship between average extended territorial per capita CO_2 emissions and increasingly rural human settlement types. This is not the case for per capita CFs.

and urban areas, respectively. The average CF of urban areas fluctuates between 10.2 and 15.5 tCO_2. The average CF of rural areas fluctuates between 10.9 and 15.0 tCO_2. Overall, figure 4 suggests that there may be other, more important drivers that determine the CF of local areas than whether a human settlement type is rural or urban. The degree of rurality in this context may simply be insignificant or an effect of lower order. So what determines the CF of human settlements in the UK?

Figure 5 shows estimated relationships between a series of geo-demographic determinants and municipal CF holding other determinants constant. The top left panel identifies the impact of weekly per capita income on the per capita CF. We find that increases in the average income of municipalities increase the CF (at slightly increasing rates). Additional £600 in the average weekly income per capita determines an increase of 1 tCO_2/cap in the CF, keeping all other variables constant.

Population density (top right panel) reduces the footprint. Though statistically very significant, the reductions are quantitatively small. Decreases in CF are larger at lower densities. An increase from very low levels of density of 3000 persons per square km, reduces the CF by half tCO_2/cap, keeping everything else constant. The reduction over the whole range of the sample is less than a ton. Ruralness, controlling for other variables, also has a statistically significant (at the 5% level) but quantitatively negligible negative impact (beta $= -0.03$) on the CF.

The middle left panel shows that increases in the average household size have a strong negative effect on the CF. The reduction is larger for household sizes larger than 2.2. The middle right panel shows how increases in average household car ownership in municipalities increase the CF at increasing rates. The CF of municipalities with an average per household car ownership of 1.5 is roughly 2 and a half tCO_2 per capita
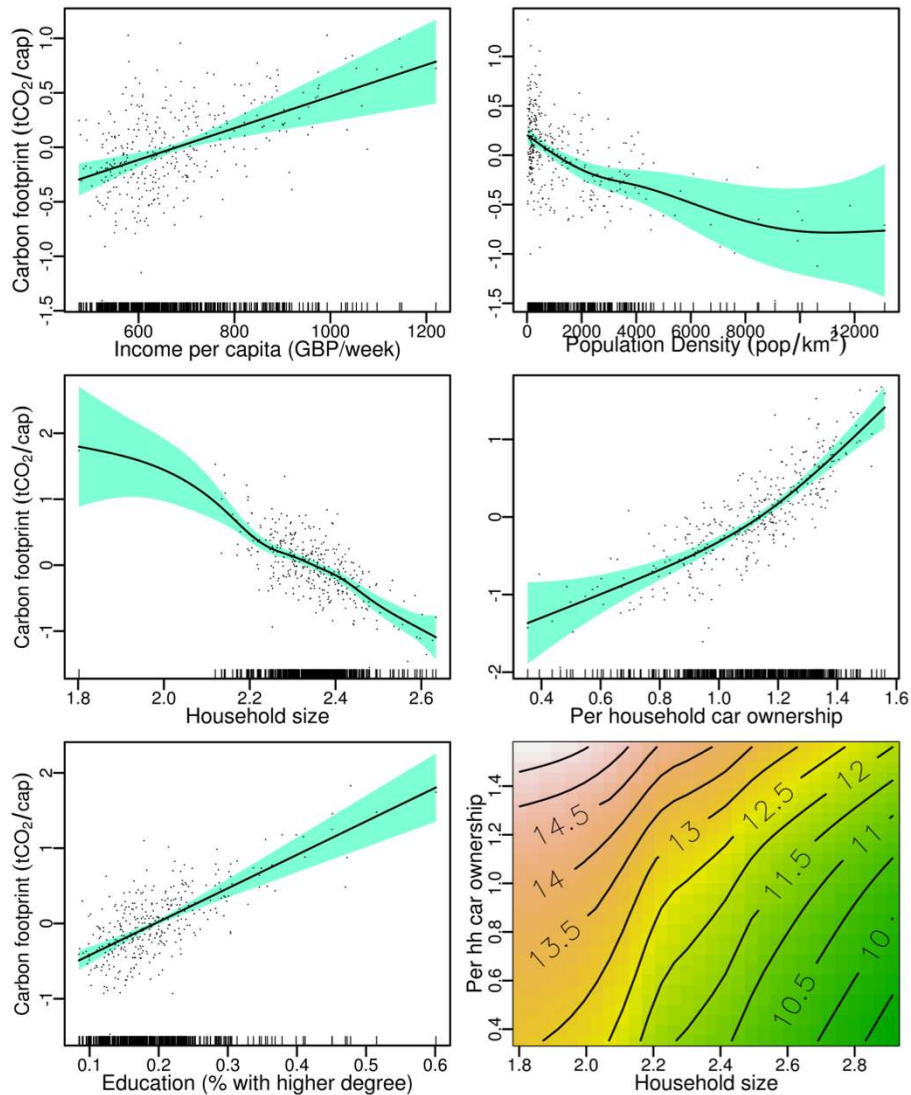
Figure 5. Estimated cross-municipal relationships between a series of geo-demographic determinants and the CF holding other determinants constant. It shows that mainly socio-economic rather than geographic and infrastructural factors strongly determine the CF. The CF increases with income, education (see footnote 13) and per household car ownership and decreases with population density and household size. Since the CF is expressed in mean deviation form, the smooth term function of the determinant, each plot represents how the CF changes relative to its mean, 12.5 t per capita, with changes in determinants. Confidence bounds, i.e., two standard errors above and below the estimate of the smooth function being plotted, are shown in each graph. The covariate to which the plot applies is displayed as a rug plot. Partial residuals, i.e., the residuals after removing the effect of all other determinants, are also plotted. The model explains 87% of the footprint variability. All coefficients are highly significant and we find no evidence of model misspecification. Detailed results and regression diagnostics are reported in the regression in the SI (available at stacks.iop.org/ERL/8/035039/mmedia).

higher than for a municipality with an average per household car ownership of 0.5.

Education[13], shown in the bottom left panel in figure 5, has a strong positive impact on per capita CFs with linear relationship. Throughout the range of education levels (proportion of educated people), (0.08, 0.60), CF increases by more than 1 tCO_2/cap. The bottom right panel in figure 5 shows the contour plot views of the predicted CF for the

available range of household size and car ownership. The plot highlights the nonlinearities and the significant quantitative impacts of the two determinants on the CF. Heating degree days, controlling for all other determinants, is only marginally statistically (p-value: 0.076) and quantitatively significant (with changes over the sample range limited to within a quarter of a ton). See the SI for details.

4. Discussion

In this letter, we analyse CFs of 434 municipalities in the UK grouped into five categories of human settlements and compare them with extended territorial CO_2 emission

---

[13] Education is defined as the proportion of municipal residents holding higher degree qualifications (at least what is known in the UK as level 4, which, according to the UK government, www.gov.uk, includes Certificate of Higher Education, Diploma of Higher Education, bachelor's degrees, master's degrees and doctoral degrees).

estimates. To derive CF estimates, we develop a model that explicitly links global supply chains to local consumption activities. Such an analysis will necessarily give rise to a variety of uncertainties. For our multi-regional input–output model, an explicit formal uncertainty analysis has been carried out (Lenzen *et al* 2010). For consumption-based emissions at the national level the relative standard deviation is moderate with around 5% of the total estimate. This moderate variation is due to averaging effects. At the sector level these uncertainties can therefore be much larger (Wiedmann *et al* 2008). The effects of the high regional aggregation in our global multi-regional model on national consumption-based CFs were not covered in depth in these studies. Andrew *et al* (2009) focus on this type of error in their analysis based on the GTAP dataset. The study highlights that different types of multi-regional models with a small number of regions can already approximate the results of multi-directional, multi-regional input–output models with full regional resolution within a range of ±5%.

Uncertainties associated with local consumption estimates are much less explored in our model as well as in the literature—mainly due to a lack of adequate information to perform such an analysis. However, our methodology for downscaling local consumption has been designed with a view of minimizing data-related uncertainties by allowing for the usage of the best available data at a given aggregation level. In particular, local consumption patterns are estimated based on a rich geo-demographic classification with 61 different lifestyles. Estimates are 'localized' based on local statistics partially overcoming the assumption of homogeneous behaviour within a lifestyle regardless of location. Lifestyle groups consume bundles of goods and services from large clusters or even all sectors of the economy. Similar to estimates at the national level, uncertainties for individual lifestyle groups or the entire population of a particular local area (which is essentially a mix of lifestyle groups) will be reduced by the associated averaging effects. With the arrival of similar studies for the UK or other countries, future research should further explore uncertainties associated with downscaling information.

Having these various uncertainties in mind, the following key insights can be derived from our analysis: First, lifestyle and consumption-related CO_2 emissions as captured in the CF are much more homogeneous across space than territorial emissions, which are characterized by the distinct economic role of human settlements in production networks. The scale of activity and associated energy end-use of major industrial plants can be orders of magnitudes higher than for individual households or small service enterprises. These major industrial activities are often highly concentrated and can have an overwhelming influence on the territorial emission profile of a particular local area. We also find evidence for high emission profiles of areas characterized by a high density of service sector activities, but this is mostly explained by the chosen procedure for normalizing emissions for this comparison rather than high absolute CO_2 emissions of the area itself (see footnote 12). In contrast, CF estimates are accounted for at the point of final

consumption with the main focus on households. Households are numerous, small actors of similar size. While at the level of individual households differences in activity levels may lead to differences in CFs of a factor of ten (Weber and Matthews 2008), CFs at the high end of that scale will usually be balanced out by more moderate footprints of the remaining households in municipal areas[14].

Second, the large majority of local areas—regardless whether rural or urban—tend to be net importer of emissions, i.e. their CF is larger than their extended territorial CO_2 emissions. Elsewhere we show for the national level that the growing specialization of the UK economy on services since the early 1990s has been associated with growing CO_2 imports from industrial products manufactured in other parts of the world (Baiocchi and Minx 2010). This growing reliance on imported goods is a background trend for the observed reliance of UK municipalities on their global hinterlands. Nevertheless, even within a net CO_2 importing economy like the UK, key production-oriented areas have larger extended territorial CO_2 emission compared to their CF. These areas are pre-dominantly located in the local hinterlands of urban settlement types.

Third, metropolitan living may but does not have to be associated with a higher CF (cf Heinonen *et al* 2011). The CF of human settlements across density gradients remains mostly unexplored in the literature due to a lack of evidence for rural settlement types. Our study makes an attempt to provide some first insights. On average, the three urban settlement types have slightly lower CFs than the two rural settlement types included in our study, but within each of these groups large variation exists. Hence, there is no clear influence of density gradients on our CF results. We find evidence for 'high carbon lifestyles' relative to the UK average in both rural and urban areas, but our analysis shows that the CF relative to extended territorial emissions is consistently larger in urban areas. The most urbanized settlement type (i.e. settlement type 'Major Urban') in our study includes the municipalities with both the highest and lowest CF at the same time. Broad brushed conclusions with regard to the CF associated with broad density classes of human settlements cannot be easily made. Instead the CF of local areas needs to be carefully analysed under full consideration of the various socio-economic, geographic and infrastructural drivers.

Fourth, at the municipality level the variation in the CF across space can be largely explained by a small set of socio-economic determinants: income, household size, car ownership and education. When controlling for other variables, changes in income levels across municipalities have a strong impact on the CF as shown in other studies (e.g. Heinonen *et al* 2011, Wiedenhofer *et al* 2011), but are not dominating the results. Some of the other determinants

---

[14] The CF of the 61 lifestyles underpinning this analysis differs only by a factor of three (Minx *et al* 2009). This factor of three marks the outer range of possible differences in CF across areas in our modelling framework. Moreover, further averaging effects will be at work, because many different lifestyle groups live within a municipality. There is a wealth of research showing that people with a shared socio-economic profile tend to cluster in space (Schelling 1969), but such clustering processes tend to take place at a much finer spatial level (e.g. neighbourhoods).

are at least equally important. Note that some of these variables—like car ownership—are likely to capture broader aspects of lifestyles and should not be interpreted literally. It seems that a much broader understanding of lifestyles beyond income may be important for future progress in understanding local CFs. Minx and Baiocchi (2009) highlighting the potential value of geo-demographic approaches.

Fifth, the impact of variables capturing infrastructural and geographic conditions—population density and the degree of ruralness of human settlement types—is very limited. Other variables such as heating degree days are insignificant for the CF as a whole. Our analysis therefore suggests that at the spatial level of the present analysis macro-trends are driven by socio-economic variables. However, there may be significant variation within the local areas analysed. It is much more likely that at finer spatial scales the intricate interactions between lifestyles and the available infrastructure can be captured. Geographic and infrastructural effects on the CF may be stronger for analysis with higher spatial detail. Comparisons between urban areas on global scale also show significant effects of population density on energy use, an effect that is lost when the analysis is restricted to geographically more limited regions (Newman and Kenworthy 1989, Baur *et al* 2013). The spatial scale on which infrastructure and geographic conditions become relevant in comparative research is hence an important avenue for deepening the understanding of the CF of human settlements in future research. The methodology proposed here could facilitate such an analysis.

A more in-depth understanding of the relationship between infrastructure and lifestyles in shaping the CF is also crucial in order to deepen the understanding of policy applications at the local level. In general, the CF as a metric with global system boundaries can only be addressed through vertical integration from the local to the international level in a multi-level governance approach. The influence of local decision-making on the CF is limited, but largest in the area of housing and transport, where spatial planning, transport demand and transport supply measures can reduce the demand for energy or materials and associated direct as well as supply chain CO_2 emissions (e.g., Creutzig *et al* 2012). A series of case studies in the UK have demonstrated this case (Barrett and Dawkin 2008, Owen *et al* 2008). Our analysis highlights the importance of socio-economic factors, which need to be taken into account in planning applications. How much influence this can have on the overall footprint depends on how much infrastructures can shape lifestyles. The exploration of this relationship remains an important area for future research.

References

Andrew R *et al* 2009 Approximation and regional aggregation in multi-regional input–output analysis for national carbon footprint accounting *Econ. Syst. Res.* **21** 311–35

Baiocchi G and Minx J C 2010 Understanding changes in the UK's CO_2 emissions: a global perspective *Environ. Sci. Technol.* **44** 1177–84

Baiocchi G *et al* 2010 The impact of social factors and consumer behavior on CO_2 emissions in the UK: a panel regression based on input–output and geo-demographic consumer segmentation data *J. Indust. Ecol.* **14** 50–72

Barrett J and Dawkin E 2008 *Carbon Footprint of Housing in the Leeds City Region: A Report Commissioned by the Environment Agency* (York: Stockholm Environment Institute)

Baur A, Thess M, Kleinschmit B and Creutzig F 2013 Urban climate change mitigation in Europe—looking at and beyond the role of population density *J. Urban Plan. Dev.* at press (doi:10.1061/(ASCE)UP.1943-5444.0000165)

Baynes T M and Wiedmann T 2012 General approaches for assessing urban environmental sustainability *Curr. Opin. Environ. Sustain.* **4** 458–64

Chavez A and Ramaswami A 2011 Progress toward low carbon cities: approaches for transboundary GHG emissions' footprinting *Carbon Manag.* **2** 471–82

Chavez A and Ramaswami A 2013 Articulating a trans-boundary infrastructure supply chain greenhouse gas emission footprint for cities: mathematical relationships and policy relevance *Energy Policy* **54** 376–84

Chavez A *et al* 2012 Implementing trans-boundary infrastructure-based greenhouse gas accounting for Delhi, India *J. Indust. Ecol.* **16** 814–28

C40, ICLEI *et al* 2012 *Global Protocol for Community-Scale Greenhouse Gas Emissions* (C40 Cities Climate Leadership Group and ICLEI Local Governments for Sustainability in collaboration with World Resources Institute, World Bank, UNEP, and UN-HABITAT)

Covenant of Mayors 2010 *How to Develop of Sustainable Energy Action Plan (SEAP)—Guidebook* (Brussels: Publication Office of the European Union)

Creutzig F, Mühlhoff R and Römer J 2012 Decarbonizing urban transport in European cities: four cases show possibly high co-benefits *Environ. Res. Lett.* **7** 044042

DEFRA and AEA Teachnologies 2006 *Local and Regional CO_2 Emissions Estimates for 2004 for the UK* (London: DEFRA)

Druckman A and Jackson T 2009 The carbon footprint of UK households 1990–2004: a socio-economically disaggregated, quasi-multi-regional input–output model *Ecol. Econ.* **68** 2066–77

Druckman A *et al* 2008 A geographically and socio-economically disaggregated local household consumption model for the UK *J. Cleaner Prod.* **16** 870–80

Duchin F 1998 *Structural Economics* (New York: Island)

Duchin F and Hubacek K 2003 Linking social expenditures to household lifestyles *Futures* **35** 61

Experian 2004 *MOSAIC United Kingdom: The Consumer Classification for the UK* (Nottingham: Experian Ltd)

Fons-Esteve J *et al* 2008 A framework for integrated Urban monitoring in Europe *Working Paper* (Barcelona: Universitat Autonoma de Barcelona)

GEA 2012 *Global Energy Assessment—Toward a Sustainable Future* (Cambridge: Cambridge University Press) (Laxenburg: The International Institute for Applied Systems Analysis)

Harris R *et al* 2005 *Geodemographics, GIS and Neighborhood Targeting* (Chichester: Wiley)

Heinonen J and Junnila S 2011a Case study on the carbon consumption of two metropolitan cities *Int. J. Life Cycle Assess.* **16** 569–79

Heinonen J and Junilla S 2011b Implications of urban structure on carbon consumption in metropolitan areas *Environ. Res. Lett.* **6** 014018

Heinonen J *et al* 2011 Dense downtown living more carbon intense due to higher consumption: a case study of Helsinki *Environ. Res. Lett.* **6** 034034

Hillman T and Ramaswami A 2010 Greenhouse gas emission footprints and energy use benchmarks for eight US cities *Environ. Sci. Technol.* **44** 1902–10

Jones C M and Kammen D M 2011 Quantifying carbon footprint reduction opportunities for US households and communities *Environ. Sci. Technol.* **45** 4088–95

Kennedy C *et al* 2009 Greenhouse gas emissions from global cities *Environ. Sci. Technol.* **43** 7297–302

Kennedy C *et al* 2010 Methodology for inventorying greenhouse gas emissions from global cities *Energy Policy* **38** 4828–37

Kennedy C *et al* 2011 Greenhouse gas emission baselines for global cities and metropolitan regions *Cities and Climate Change: Responding to an Urgent Agenda* ed D Hoornweg, M Freire, M J Lee, P Bhada-Tata and B Yuen (Washington, DC: The World Bank) chapter 2

Kennedy S and Sgouridis S 2011 Rigorous classification and carbon accounting principles for low and zero carbon cities *Energy Policy* **39** 5259–68

Larsen H N and Hertwich E G 2009 The case for consumption-based accounting of greenhouse gas emissions to promote local climate action *Environ. Sci. Policy* **12** 791–8

Larsen H N and Hertwich E G 2010a Identifying important characteristics of municipal carbon footprints *Ecol. Econ.* **70** 60–6

Larsen H N and Hertwich E G 2010b Implementing carbon-footprint-based calculation tools in municipal greenhouse gas inventories *J. Indust. Ecol.* **14** 965–77

Lenzen M and Peters G M 2010 How city dwellers affect their resource hinterland—a spatial impact study of Australian households *J. Indust. Ecol.* **14** 73–90

Lenzen M and Treloar G 2005 Endogenising capital: a comparison of two methods *J. Appl. Input–Output Anal.* **10** 1–11

Lenzen M *et al* 2010 Uncertainty analysis for multi-region input–output models: a case study of the UK's carbon footprint *Econ. Syst. Res.* **22** 43–63

Lin J *et al* 2013b Using hybrid method to evaluate carbon footprint of Xiamen City, China *Energy Policy* **58** 220–7

Lin T *et al* 2013a Greenhouse gas emissions accounting of urban residential consumption: a household survey based approach *PLoS One* **8** e55642

Longley P A 2012 Geodemographics and the practices of geographic information science *Int. J. Geogr. Inf. Sci.* **26** 2227–37

Met Office 2011 *UKCP09: Gridded Observation Data Sets* (Exeter: Met Office)

Miller R E and Blair P D 2009 *Input Output Analysis: Foundations and Extensions* (Cambridge: Cambridge University Press)

Minx J C and Baiocchi G 2009 Time use and sustainability *Handbook for Input–Output Economics in Industrial Ecology* ed S Suh (Dordrecht: Springer) pp 819–46

Minx J C *et al* 2009 Input–output analysis and carbon footprinting: an overview of applications *Econ. Syst. Res.* **21** 187–216

Minx J C *et al* 2011 *Developing a Pragmatic Approach to Assess Urban Metabolism in Europe: A Report to the European Environment Agency. TU Working Paper 01/2011* (Berlin: Technische Universität Berlin and Stockholm Environment Institute)

Newman P W G and Kenworthy J R 1989 *Cities and Automobile Dependence: A Sourcebook* (Aldershot: Gower Technical)

Owen A *et al* 2008 *Ashford's Carbon Footprint: Now and in the Future* (York: Stockholm Environment Institute)

Paloheimo E and Salmi O 2013 Evaluating the carbon emissions of the low carbon city: a novel approach for consumer based allocation *Cities* **30** 233–9

Peters G P *et al* 2011 Growth in emission transfers via international trade from 1990 to 2008 *Proc. Natl Acad. Sci.* **108** 8903–8

Petsch S *et al* 2011 Modeling, monitoring, and visualizing carbon footprints at the urban neighborhood scale *J. Urban Technol.* **18** 81–96

Ramaswami A *et al* 2008 A demand-centered, hybrid life-cycle methodology for city-scale greenhouse gas inventories *Environ. Sci. Technol.* **42** 6455–61

Ramaswami A *et al* 2011 Two approaches to greenhouse gas emissions foot-printing at the city scale *Environ. Sci. Technol.* **45** 4205–6

Ramaswami A *et al* 2012 Carbon footprinting of cities and implications for analysis of urban material and energy flows *J. Indust. Ecol.* **16** 783–5

Schelling T C 1969 Models of segregation *Am. Econ. Rev.* **59** 488–93

Sinden G *et al* 2011 International flows of embodied CO_2 with an application to aluminium and the EU ETS *Clim. Policy* **11** 1226–45

UN-HABITAT 2011 *Cities and Climate Change, Global Report on Human Settlements 2011* (London: UN-HABITAT)

WBCSD and WRI 2004 *The Greenhouse Gas Protocol—A Corporate Accounting and Reporting Standard* (Geneva: World Business Council for Sustainable Development and World Resources Institute)

Weber C L and Matthews H S 2008 Quantifying the global and distributional aspects of American household carbon footprint *Ecol. Econ.* **66** 379–91

Weisz H and Duchin F 2006 Physical and monetary input–output analysis: what makes the difference? *Ecol. Econ.* **57** 534

Weisz H and Steinberger J 2012 City walls and urban hinterlands. The importance of system boundaries *Energizing Sustainable Cities: Assessing Urban Energy* ed A Grübler and D Fisk (London: Earthscan)

White C *et al* 2010 The total carbon footprint of Stockton-on-Tees Borough Council, England, UK *The Sustainability Practitioner's Guide to Input–Output Analysis* ed J Murray and R Wood (Champaign, IL: Common Ground Publishing LLC) chapter 6, pp 73–82,

Wiedenhofer D *et al* 2011 Spatial and socio-economic drivers of direct and indirect household energy consumption in Australia *Urban Consumption* ed P Newton (Victoria: CSIRO Publishing)

Wiedmann T and Minx J 2008 A definition of 'carbon footprint' *Ecological Economics Research Trends* vol 2, ed C C Pertsova (New York: Nova Science Publishers) chapter 1, pp 55–65,

Wiedmann T *et al* 2008 Uncertainty analysis of the UK-MRIO model—results from a Monte-Carlo analysis of the UK multi-region input–output model *Report to the UK Department for Environment, Food and Rural Affairs by Stockholm Environment Institute at the University of York and Centre for Integrated Sustainability Analysis at the University of Sydney* (London: DEFRA)

Wiedmann T *et al* 2010 A carbon footprint time series of the UK—results from a multi-region input–output model *Econ. Syst. Res.* **22** 19–42

Wright L A *et al* 2011 Carbon footprinting for climate change management in cities *Carbon Manag.* **2** 49–60