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# Carbon Footprints

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# Unravelling the drivers of European urban and rural carbon footprints over time

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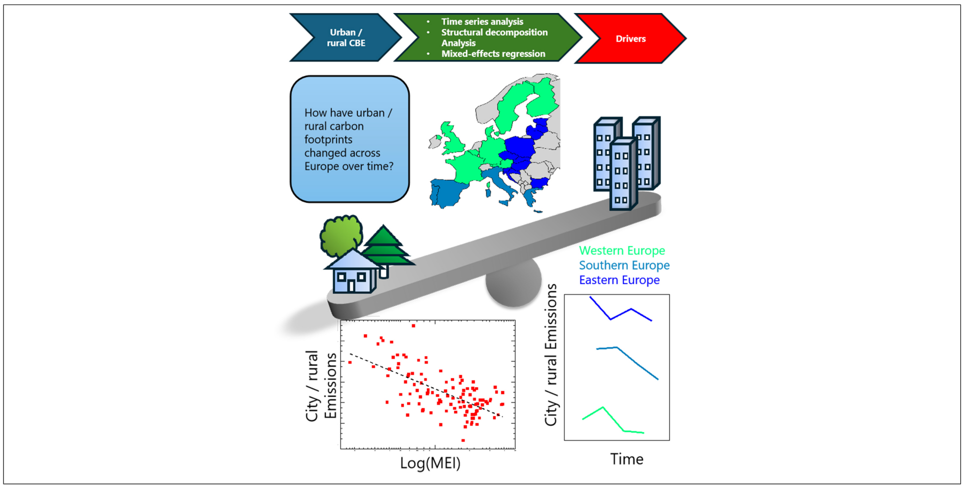


## Abstract

Although urban density is expected to reduce emissions related to local transportation and energy consumption, consumer carbon footprints, which cover all life cycle emissions caused by the consumption of goods and services, tend to be highest in cities and lower in rural areas. However, there is little research into how this might be changing over time. As such, longitudinal studies are important to understand factors driving emission changes, trajectories, and transitions not apparent from the results of a single year. Here, we conduct personal consumption-based emission footprints at different levels of urban density for European countries between 1994 and 2020. The results show a generally declining picture of emissions and with inter-country convergence, although at levels consistently above those required to hit international emission targets. Emissions are higher in cities in Southern and Eastern Europe, with slight decreases in these differences over time, but lower in Western Europe. The driving forces of changes in relative emissions are unravelled using structural decomposition analysis, which highlights differing pictures between the three regions. This is further illuminated through the key densification sectors

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of transport and energy, which implies that, despite lower emissions overall, there has been a strong decrease in the carbon efficiency from urban living in Western Europe. The work contributes to understanding the role of urban type on emissions and unravels distinct pictures that might reflect differences in development trajectories over time.

## INTRODUCTION

Consumption is a key driver of increasing global greenhouse gas emissions[1]. The use of consumption-based emission footprints, such as those based on the environmentally extended input-output (EEIO) method, are consequently important for allowing responsibility of emissions to be tracked across boundaries[2]. In the more affluent countries, consumption-based emissions, also called carbon footprints, are often significantly higher than when traditional territorial assessments are used[3,4] and underline the global emissions hidden through the movement of goods and services from one region to another[5,6]. This reflects profound inequalities in carbon footprints; 50% of the global carbon dioxide emissions are caused by the most affluent 10%, and the 50% least affluent only cause slightly over 10% of emissions[7].

By allowing similar methodologies to be applied across spatial scales, consumption-based emissions highlight how individual choices sit within the context of broader social and structural factors at the local, national, and global level[8]. It also affords a comparability between disparate areas in a way that is not possible using traditional territorial based assessments[9]. By looking across differences in socio-economy, demography and geography, influences on patterns and distributions of emissions can be unravelled[10,11].

In these studies, questions on how and whether the local urban environment can influence emissions have been prominent[12,13]. A key hypothesis has been that, by allowing more efficient pooling of resources through mass-transport and more efficient energy use, cities have the potential to partly lower per capita emissions. But both incomes and consumption possibilities tend to be higher in denser areas[8].

This competition between greater income and consumption possibilities against resource pooling may also not be static over time or as income levels, production technologies, consumption patterns, and even urban environments change. It has long been theorised that as incomes rise, greater proportions are directed towards service-based activities, which often have a lower impact when measured in emissions per unit spent. This idea is similar to the so-called environmental Kuznets curve[14], which more generally holds that rising expenditure (or development) is first associated with greater environmental harms before reversing, although evidence for this is currently under debate[15-17]. Some studies have suggested that this only happens on top of the more emissions-intensive mandatory consumption of shelter, transport and food, and therefore the lower overall emissions-intensity of the consumption of the more affluent is an illusion created by the luxury consumption part beyond the reach of the less affluent. Differing emissions trajectories may also be seen when different accounting principles are used[18].

Many consumption-based emission studies have so far been conducted to cover a single year. Whilst work has shown the variations in consumption-based emissions across geographical scope, such as within a single country[10] or across (parts of) a continent, exploration is also needed into how emissions and their drivers vary across time[11,19]. This is important since any relationship between urban density and emissions will itself derive from a variety of drivers that are themselves not static. Thus, these drivers can’t purely be elucidated simply by comparing countries that may profoundly differ from one another in geography, climate, or culture. Furthermore, lifestyles change along with technological development, and new technologies can bridge the gap between urban and rural areas in terms of purchasing opportunities.

There are a number of studies that have considered the differences in carbon footprints across Europe. Ivanova and Wood combined household budget surveys (HBS) microdata with emissions derived from the Exiobase input-output database to understand the distribution of emissions across Europe related to income[20]. The results showed that, across all countries, emissions are highly unequal, with only 5% of footprints below 2.5 tonnes $CO_2$e per capita and with the top 10% of incomes contributing to over a quarter of Europe's climate footprint. Turning to the urban gradient, the same authors looked at the differences in footprints across regions at the nomenclature of territorial units for statistics (NUTS2) level[21]. This was combined with a regression model that suggested that differences in urban density were only important in explaining differences in land transport. However, here it is also likely that the NUTS classification is not aligned with or able to capture differences in urban density, with cities and the surrounding hinterland enclosed within the same region. The author's themselves state that there are minor differences in urban density across their dataset.

This notwithstanding, a systematic review by Ottelin *et al.* reported that in general, consumption-based emissions in cities are not lower than rural areas[8]. This was found across a wide variety of countries and encompassed a range of development levels. Other work has been more contextual, with different effects based on geographical region[22] or city size[23]. In a European context, research has both shown higher emissions amongst city residents in many areas of Europe, but lower levels in some Western areas, whilst also indicating that such effects are minor compared to the differences between countries[22]. When controlling for other variables, the same paper found that on average per capita emissions are 7% lower in rural areas across the continent. However, higher emissions amongst rural residents of affluent countries have also been seen in studies from the UK[24] and US[25].

There is also a more limited pool of previous studies that consider the urban gradient over time. In China, emissions were seen to rise with the degree of urbanisation, mainly because of rising incomes[26,27]. The global analysis of the years 2010-2015 by Yuan *et al.* similarly found higher emissions for urban residents, but with a convergence over time, particularly in developing regions[28]. The paper also stated that high-income regions are responsible for the majority of household emissions. In this context, further research focusing on the impacts of urbanisation and the urbanisation process in developed countries is therefore needed.

The paper is organised around the following two research questions:

1. How have personal carbon footprints developed for urban and rural residents across different regions of Europe?

2. What drivers of any (relative) changes can be elucidated from the data?

Here, we contribute to the discussion by conducting a time series analysis of personal carbon footprints across Europe, focusing on the effects of degree of urbanisation. We use consumption expenditure data from Eurostat for the years 1994-2020 and for 29 European countries combined with the direct emissions from fuel combustion (also used for district heating), air travel related emissions based on kilometres travelled (including high altitude effects), and with the rest of the indirect emissions embodied in other consumption estimated with the Exiobase multi-region input-output (MRIO) model[29]. Furthermore, we use structural decomposition analysis (SDA) to trace the factors behind what changes are observed, and particularly behind the relative changes across the urban-rural continuum.

The results show distinct patterns across the continent. In the richer west-north axis, rural footprints tend to exceed those in more urbanized areas, whereas towards the south or east the pattern is the opposite. A limited levelling off of the footprint differences is also observed along with some evidence of decreasing income disparities and diminishing resource efficiency of urban living in Western Europe. Additionally, we also show to what extent emissions have been in accordance with estimated carbon budgets for agreed levels of warming across countries, time, and urban type. Finally, we align on an apparent empirical relationship between the relative difference in urban and rural emissions and the overall affluence of the country.

## DATA AND METHODS

Emissions arising from governmental expenditure or capital investment are not included in the analysis. Household consumption typically makes up around 50%-70% of an individual's carbon footprint[30]. Removing emissions from public expenditure still lowers emissions significantly compared to if these were directly attributed to residents. However, data was not available to explain how this should be applied to residents based on where they live, and so was not included to allow the results to isolate the proportion of emissions that could easily be compared between urban and rural households. Consumption expenditures were computed using publicly available HBS by degree of urbanisation (hbs_exp_t136; hbs_str_t226) obtained from Eurostat. The classification methodology for this involves defining urbanisation into three categories (cities, towns and suburbs and rural areas) using 1 $km^2$ grid cells. As discussed in the 2021 methodology[31], this is based on defining continuous areas as either high or moderate-density clusters, with high-density clusters requiring a total population of at least 50,000 inhabitants and a population density of at least 1,500 inhabitants per $km^2$. Medium-density clusters require in turn at least 5,000 inhabitants and a population density of at least 300 inhabitants per $km^2$. All other grid cells are classified as rural areas. Cities are required to have at least 50% of their population in high-density clusters, whilst for towns and suburbs, less than 50% of the population must be in high-density clusters with no more than half in rural grid cells. Rural areas have more than 50% of their population in rural grid cells.

The HBS data was linked to emission intensities for each country and each year, which were derived from the Exiobase model[29]. Exiobase includes a time series extending back to 1995. Note that applied emission factors for each country were an average of emission intensities for all countries, weighted by the proportion of expenditure by households of each country using the original household demand vectors from Exiobase. This accounted for the purchase of products and services across national borders. HBS surveys are conducted in general every 5 years with three different classifications of urban density: cities, towns and suburbs and rural areas. Capital investments from households were not included as they are not included in the HBSs and due to a lack of data to support separating these based on degree of urbanisation. The HBSs are available in the Classification of Individual Consumption by Purpose (COICOP) classification, and these were aligned with Exiobase emission categories using a slightly modified concordance matrix of Ivanova and Wood[20], the fuel mix of the car fleet (Eurostat) and the breakdown of solid fuels (Eurostat energy balances). A heat map showing the deviations from the initial concordance matrix is included as part of the supporting data.

The processing stages involved taking the original HBSs resolved by degree of urbanisation, gap-filling where needed using linear interpolation across years for the same country and urban-type, before all expenditure data was converted into basic prices (naio_10_cp15). The initial concordance matrix was used to then convert to Exiobase categories. Modifications to this were made in two general respects. The concordance matrix has fixed values for energy categories (heating and electricity), but these were modified so that shares of fuel were derived from data in the Eurostat energy balances. The concordance matrix was also modified for air travel - calculated outside of the EEIO approach - and package holidays, where a split was made between accommodation and air travel.

Emissions associated with waste are not included due to its low overall importance and the possibility of the extremely large emissions for some countries biasing the results. This decision was based on the observation

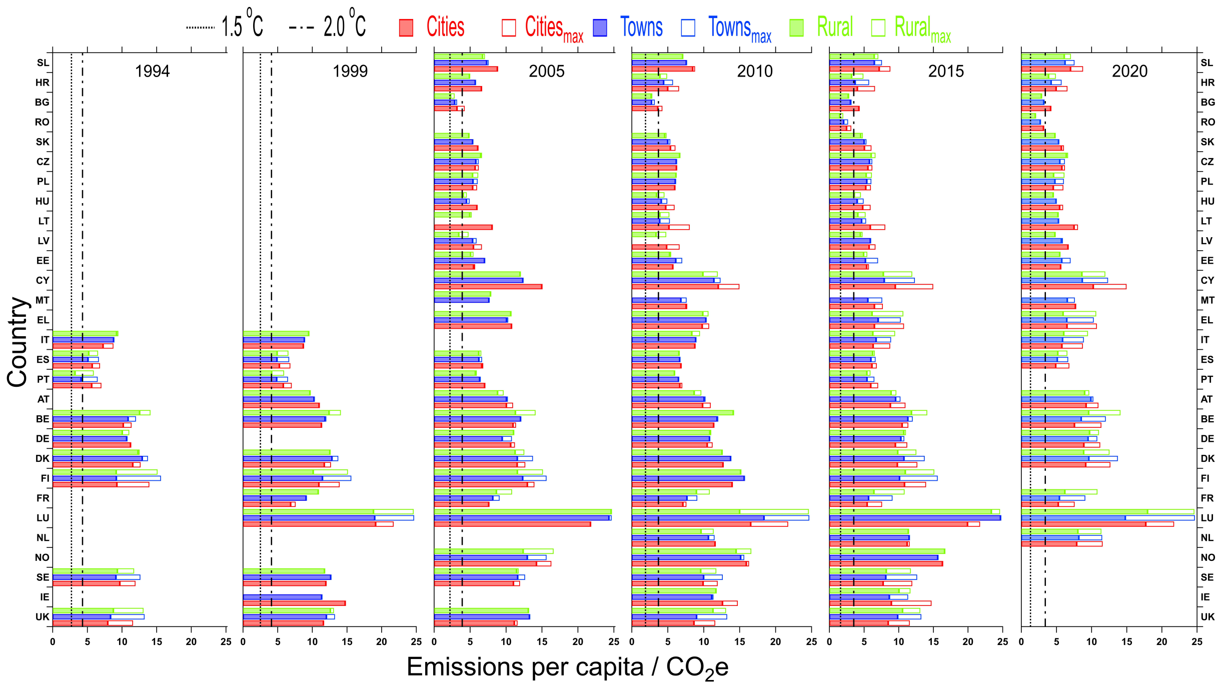


**Figure 1.** Absolute emission time series for European countries by degree of urbanisation. The graphs show per capita household emissions for residents of cities, towns and suburbs and rural areas in red, blue, and green, respectively, for the years in which household budgets were conducted between 1994 and 2020. Unfilled bars represent the maximum calculated emissions for each urban type in each country. For each year, approximate per capita carbon budgets for 1.5 and 2.0 °C levels of warming are included as vertical lines.

of large variability between years for a small group of countries and is discussed further in the study limitations. Interpolation was also used to provide data for countries with completely missing or highly incomplete HBSs covering a single year (Italy; 2005, Germany 1999), so long as data was available from the preceding and subsequent cohorts. One further case was Latvia, for which data was missing for towns in 2010. Here, the average relative change between 2005 and 2010 for cities and rural areas was used as a scale factor for the 2005 values. This was done to minimise effects on the regional averages, and such data was not included in Figure 1.

Only country-year combinations with sufficient data in the HBS were included and only countries with data across urban types was included in the ensemble analysis. These requirements differed between Figures 2-4 since the latter did not require results for towns and suburbs. The country abbreviations used, alongside the countries included in the analyses for Figures 2-4 are displayed in Supplementary Tables 1 and 2, respectively. Electricity emission intensities were calculated based on national grid emission intensities, derived from an EMBER time series (Global-Electricity-Review-2025). This was in units of g $CO_2e$/kWh and converted to expenditure units using Eurostat price data. District heating emission factors were determined through Exiobase, but the first tier of district heating emissions was determined using Eurostat energy balances based on the share of heat energy produced from different energy carriers. Direct emissions were added using price statistics from Eurostat and average weekly oil bulletins and emission factors obtained from the British government's emission factors conversion data. However self-sourced fuels (such as biomass) are not considered. A separate method was used for air travel. Emissions per passenger km were first calculated using data on global passenger km (World Airlines Traffic and Capacity dataset) and overall emissions[32] (including high altitude effects). To convert to emissions per euro, separate Eurostat data on total passenger km and total expenditure within Europe were used (avia_tppa; tour_dem_extr), with the assumption that these values would be like flights outside of European borders.

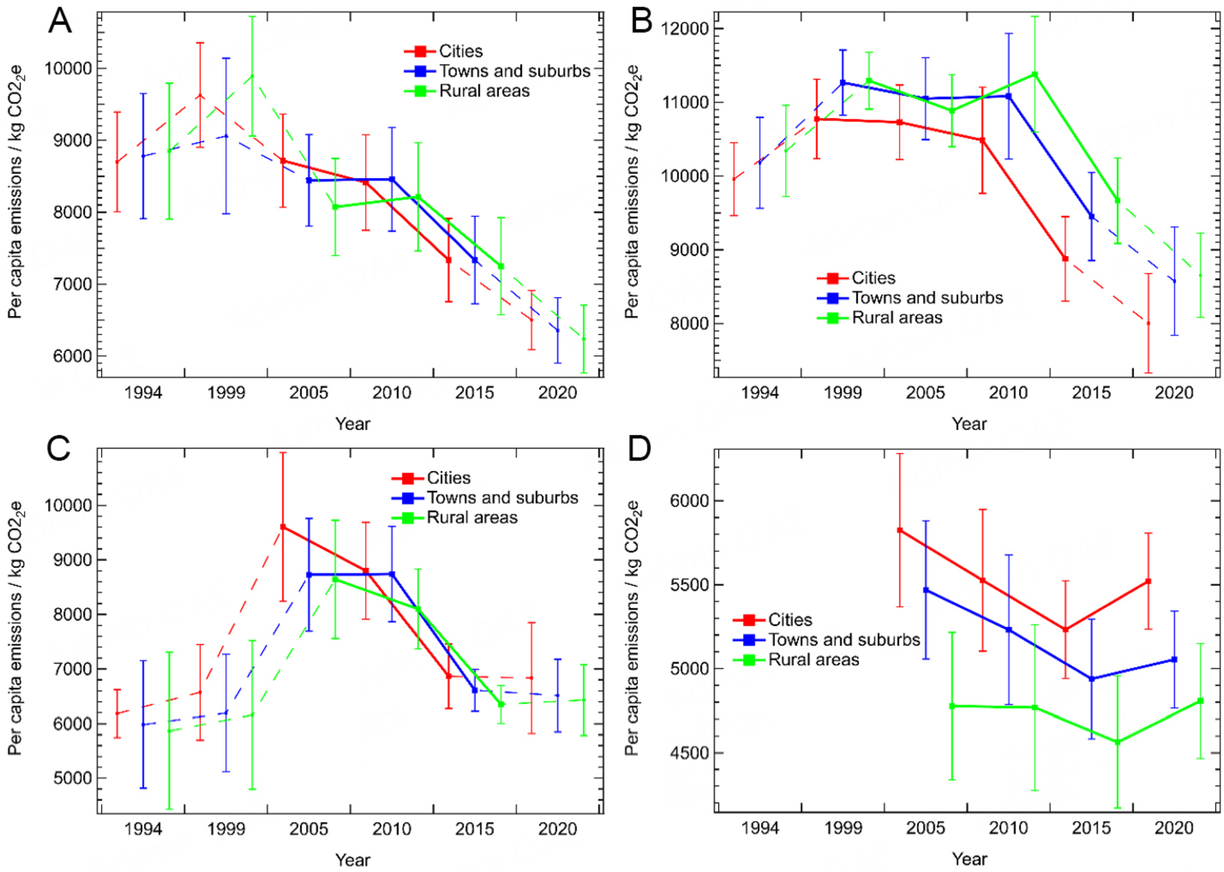


**Figure 2.** Emission averages against urban density for all of Europe (A), Western Europe (B), Southern Europe (C), and Eastern Europe (D). Emissions for city, towns and suburbs and rural residents are shown in red, blue, and green, respectively. Solid bars represent results drawn from a consistent pool of countries, with the dashed lines showing the results for a reduced pool of countries because of missing data. Error bars are calculated using the standard error on the mean.

Approximate carbon budgets were calculated using data from the 6th IPCC scientific basis report on remaining $CO_2$ budgets[33], derived from scenarios in the IPCC special report on global warming of 1.5 °C[34]. Budgets were taken using the 50% likelihood value for both 1.5 and 2.0 °C and for the year 2020. For previous years, these values were adjusted using cumulative $CO_2$ emissions (including from Land-use, Land-use change and forestry (LULUCF) and cement carbonation) from the global carbon budget report 2024[35]. This gave total $CO_2$ only carbon budgets for each year used in the current study. It was assumed in all cases that carbon neutrality would be reached in 2050, with permissible emissions divided equally between years. Emissions were assigned equally using total population estimates for each year (obtained from UN estimates) and a scaling factor of 0.6 to equalize the budget with the private consumption only. The decision to not include other greenhouse gases was a simplification. Note that the values should be taken as initial estimates for a single year only. A clear driver of the differences between years is changes in the global population between 1994 and 2020.

Regional groupings were made using unweighted averages in the main text, since the aim was to compare differences across urban types rather than to compute absolute emissions from different areas of Europe. The weighted average values used total population in the case of Supplementary Figure 1 and total population living in cities and rural areas in the case of Supplementary Figures 2 and 3.

SDA used the index-based method of Fisher as detailed by De Boer and Rodrigues[36,37]. Considering the ratio between footprints allowed grouping and comparisons between countries with otherwise large differences in

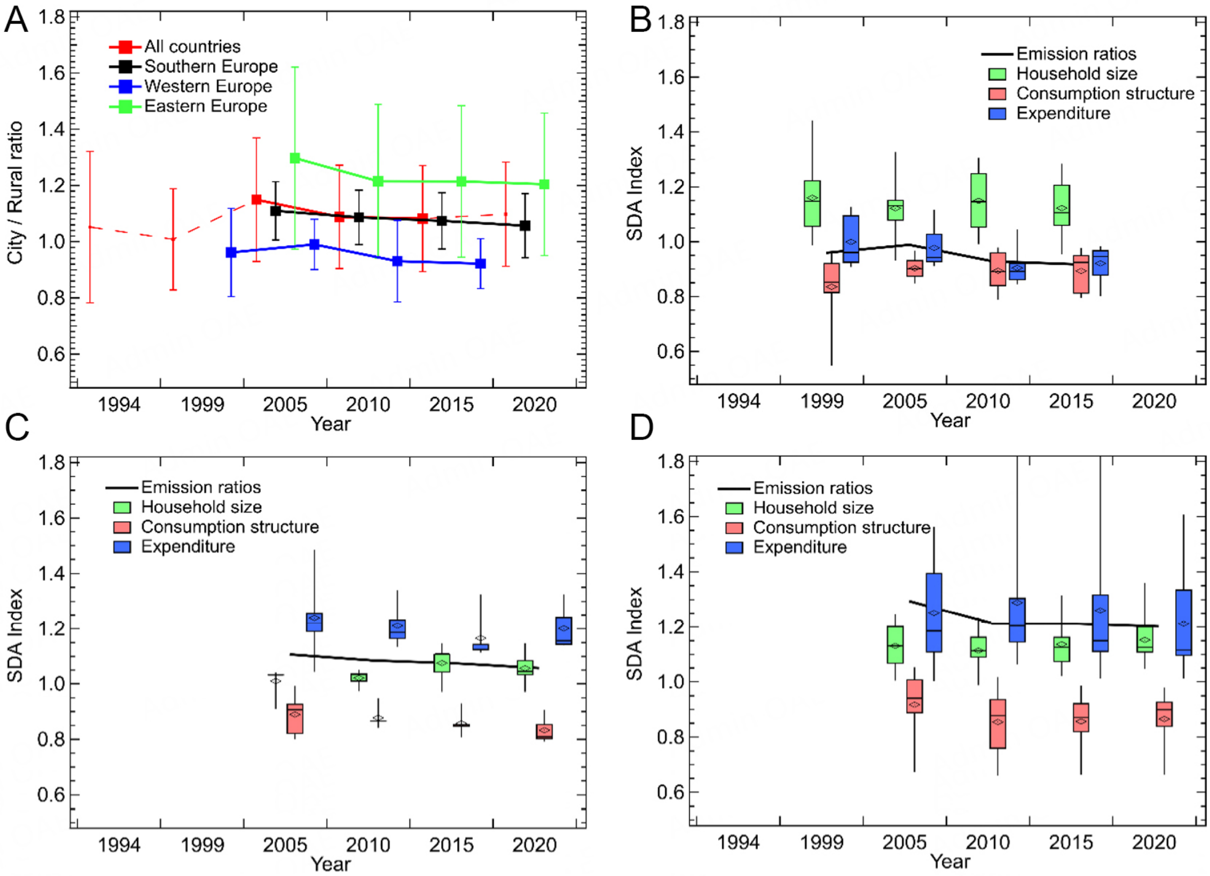


**Figure 3.** Emission ratios between urban and rural residents in Europe, grouped by geographical region (A), results of structural decomposition analysis as box plots for Western (B), Southern (C), and Eastern Europe (D), respectively. The dashed red line in (A) shows the average ratio when considering only the countries that had data in these years. Error bars are given as 1 standard deviation of the results from the respective countries in the grouping. The central line in the box plots corresponds to the median value, with the black diamond representing the mean, Whiskers extend between the minimum and maximum data points. Box plots in b-d were made for 8, 5 and 10 countries for Western, Southern and Eastern Europe, respectively, and are presented at intervals of 5 years.

emissions. Per capita emission footprints were broken down into four factors, with the calculation performed between city and rural areas in the same year. The factors considered were the overall household expenditure, structure of household consumption, household size (occupancy), and emission intensities. Note that as emissions were compared from the same country and in the same year, the value for this index was 1 in all cases. Note that for the SDA of Southern Europe, the values for Portugal in 2015 were replicated for 2020. This was taken for this single country to increase the time series until 2020. In principle, this value could also have been extrapolated, however this was too uncertain given the small number of values.

Median equivalised income (MEI) per country was obtained from Eurostat (ilc_di03) and inflation corrected to 2015. All emissions are in units of $CO_2e$ throughout the paper unless otherwise specified.

## RESULTS

### Emission time series

Figure 1 shows a time series of per capita household carbon footprints across Europe at different urban densities. Per capita emissions are shown as horizontal bar charts for each year. Countries are denoted by their two letter abbreviations according to the standard ISO 3166-1 alpha-2. Results are displayed for cities, towns and suburbs, and rural areas in red, blue, and green, respectively. Countries are included subject to

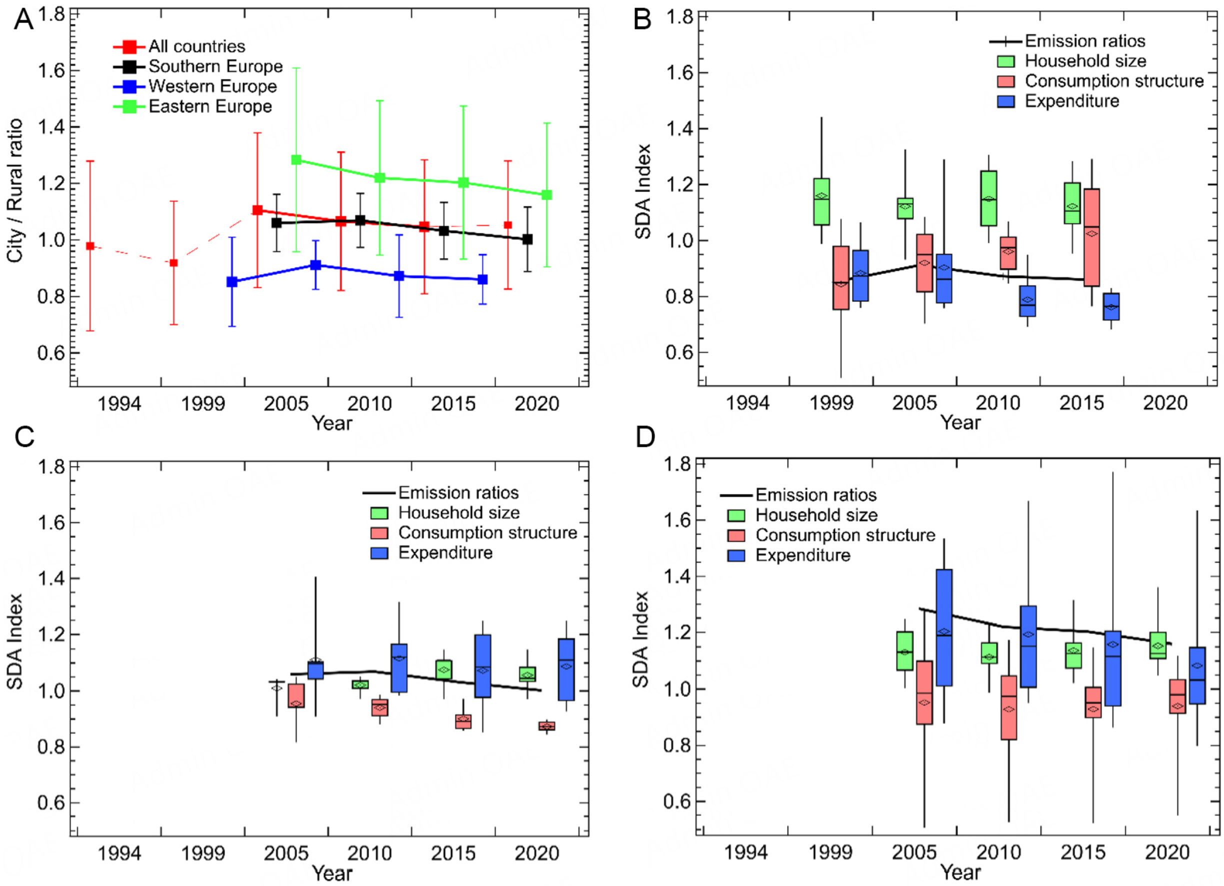


**Figure 4.** Emission ratios between urban and rural residents in Europe, grouped by geographical region, and considering only emissions from transport and energy (A), Results of structural decomposition analysis as box plots for Western (B), Southern (C), and Eastern Europe (D), respectively, considering only transport and energy, with the indices for household size, consumption structure and total expenditure shown in green, red and blue, respectively. Error bars in a are given as 1 standard deviation of the results from the respective countries in the grouping. Box plots were made for 8, 5 and 10 countries for Western, Southern and Eastern Europe, respectively, and are presented at intervals of 5 years.

data availability starting from 1994, such that those part of the more recent rounds of EU enlargement (typically in Eastern Europe) are only included from 2005. Moreover, for easier comparison, the maximum value across all years for each country-urban type is included as an unshaded bar. Full breakdowns of the per capita emissions and expenditure for each country are provided in Supplementary Figures 4-31.

Emissions have varied considerably between countries across all measured years. Emissions tend to be higher in the richer countries of Northern and Western Europe clustered at the bottom of the figure, irrespective of urban density. Indeed, differences between countries show greater variation than between different urban types. Comparing the unshaded bars suggests that in most cases maximum emissions were seen around 2005 or 2010, although there are some exceptions to this for countries in Eastern and North-Eastern Europe. For example, Latvia and Lithuania mostly have maximum emissions in 2020. Indeed, decreases across this region between 2010 and 2020 are in general very gradual across all urban types.

This notwithstanding, a second feature of the emission trajectories is the decrease in the distribution of emissions over time, mostly driven by the decreases in Western and Southern Europe since around 2005. For 2020, most results are between 3 and 7 tonnes $CO_2e$ per capita, although in this case temporary factors associated with the pandemic may also play a role. Further details, including a breakdown of emissions and time series for each country, are provided in the Supplementary Materials.

**Table 1. List of emissions of residents for cities, towns and suburbs and rural areas (denoted by the superscripts C, T and R, respectively) that are below, at or close to the levels required to meet approximate budgets for 1.5 and 2.0 °C warming targets**

| Year | 2.0 °C boundary | | | 1.5 °C boundary | | | Boundary value/tonnes $CO_2e$ | |
|---|---|---|---|---|---|---|---|---|
| | Below | Within 0.25 tonnes | Within 1 tonne | Below | Within 0.25 tonnes | Within 1 tonne | 2.0 °C | 1.5 °C |
| 1994 | $PT^{T, R}$ | | $ES^{T, R}$ | | | $PT^{R}$ | 4.3 | 2.7 |
| 1999 | | $PT^{R}$ | $PT^{T}$, $ES^{T, R}$ | | | | 4.1 | 2.5 |
| 2005 | $BG^{C, T, R}$, $LV^{R}$ | $HU^{R}$ | $HR^{R}$, $HU^{T}$, $SK^{R}$ | | $BG^{R}$ | $BG^{C, T}$ | 3.9 | 2.2 |
| 2010 | $BG^{C, T, R}$, $HU^{R}$, $LV^{R}$ | $HR^{R}$, $LT^{T, R}$ | $HR^{T}$, $HU^{T}$, $SK^{R}$ | | | $BG^{T, R}$ | 3.7 | 1.9 |
| 2015 | $BG^{T, R}$, $HR^{R}$, $RO^{C, T, R}$ | $HR^{T}$, $HU^{R}$ | $BG^{C}$, $HR^{C}$, $HU^{T}$, $LV^{R}$, $SK^{R}$, $LT^{R}$ | $RO^{R}$ | | $RO^{C, T}$ | 3.5 | 1.6 |
| 2020 | $BG^{T,R}$, $RO^{C, T, R}$ | | $BG^{C}$, $HR^{T, R}$ | | | $RO^{R}$ | 3.4 | 1.3 |

C: Cities; T: towns and suburbs; R: rural areas.

Approximate carbon budgets for 1.5 and 2.0 °C are included as black vertical lines by extrapolating current estimates backwards, as discussed in the methods section. The value for the 1.5 °C target decreased from 2.7 tonnes per capita in 1994 to 1.3 in 2020, whilst the 2.0 °C showed a decrease from around 4.3 tonnes to 3.4 tonnes $CO_2e$ by 2020. Note that these carbon budgets are approximate, not least since they apply a constant allocation to each year. They also only account for $CO_2$ emissions.

Given the uncertainties involved, a simple classification scheme was used to assess whether residents were below, around (within 0.25 tonnes) or just over (within 1 tonne) the respective carbon budgets. Table 1 provides a summary of country-urban type combinations that meet these conditions in each year.

Considered in this way, emissions in most countries were not consistent with either the 1.5- or 2-degree targets throughout the analysed period, irrespective of the degree of urbanisation. There are very few exceptions to this and none in Western or Southern Europe, apart from emissions for Portuguese residents in 1994 (Rural areas and Towns and suburbs) and 1999 (Rural areas).

Amongst the countries that participated in the 2005 cohort, only rural residents of Romania in 2015 had emissions consistent with the 1.5 °C boundary (Romania is considered only in 2015 and 2020, due to missing data in other years). Residents of Bulgaria (2005; 2010), Romania and Portugal (1994; Rural) were the only countries with emissions close to this boundary (within 1 tonne $CO_2e$) in any year.

More examples are seen using the 2.0 °C boundary, although these are also clustered around rural and town residents of Eastern and North-Eastern Europe. Romanian and Bulgarian residents had emissions consistent with the 2.0 °C boundary across all years where data was available, apart from recently for city residents in the latter case (within 1 tonne since 2015). Outside of cities, Croatian residents were also consistently below or close to this boundary, at least until 2015, as were rural residents from Hungary and rural Latvian and Lithuanian residents between 2005 and 2015, and 2010 and 2015 respectively. Typically, it was only for rural and town residents from Eastern or North-Eastern Europe that emissions were at a level close to those required to limit warming to globally agreed targets.

Understanding any trajectory for this comparison is less certain. Fewer country-urban types have emissions close to the boundaries in 2020, but it is unclear if this reflects a trend. A more general observation is that differences between urban densities are relatively minor compared to those between countries, with those in Western Europe being consistently the highest.

Clearer indications are provided by grouping countries by geography. Here, three groupings for Northern/Western, Southern, and Eastern/North-Eastern Europe were used. Figure 2 shows the average emissions for all countries considered, as well as individually for Western, Southern, and Eastern Europe, respectively. Note that for this and subsequent analysis, several countries were removed from the data due to either highly variable results (Luxembourg) or limited/missing time series data (Romania). Indeed, constructing fully consistent time series across the entire period was not possible due to missing data. The solid lines represent values drawn from a consistent pool of countries, with the countries included indicated in Supplementary Table 3. The provided error bars are given as the standard error on the mean (SEM). The dashed lines represent the averages when accounting for missing data in some countries and are included for completeness. Issues surrounding missing data are discussed in detail in the limitations section. It should further be emphasised that the values are not weighted by population, since the goal is to describe patterns seen across Europe rather than alight on absolute results for the whole continent. Alternative versions of the graphs weighted by population are shown in Supplementary Figure 1.

The data in Figure 2A shows that, when taking an average of all countries, emissions have been decreasing since 2005 for all urban types. The large decrease between 1999 and 2005, as indicated by the dashed lines, partly reflects the expansion of countries included in the analysis, since most introduced in the 2005 cohort had lower than average emissions.

It is more illustrative to turn to the countries grouped by geographical region. Any grouping of countries will in some sense be arbitrary. Those here were chosen to be large enough to partly mitigate the effects of any outliers, while allowing each to represent clear distinctions in recent histories, climate, and other factors.

Looking at Western and Northern Europe in Figure 2B, a consistent time series could be drawn of 8 countries from 1999 to 2015. Within this subset, emissions have generally been dropping since around 1999 for all urban types, although most of this decrease took place between 2010 and 2015. It is further notable that emissions in cities tend to be lower than for rural areas or towns and suburbs.

When turning to Southern Europe in Figure 2C, a consistent pool could only be drawn between 2005 and 2015, involving 5 countries. Therein, emissions again decreased irrespective of density. For the three countries with which results could be determined from 1994 (Italy, Portugal, and Spain) there is a clear peak in emissions around 2010. A further conclusion is the tendency for emissions between urban types to become more similar over time, with similar average emissions in recent years. The rate of decrease for both Western and Southern Europe appears quickest between 2010 and 2015.

The pattern of recent decrease in absolute emissions is not entirely repeated for Eastern Europe. Whereas emissions did tend to decrease between 2005 and 2015 for city residents, the data shows an increase more recently, with 2010 and 2020 values similar. This is also seen in the emission patterns for towns and suburbs. Emissions for rural residents have remained very consistent. The values are essentially unchanged between 2005 and 2010. A more modest drop in emissions is seen between 2010 and 2015, with emissions thereafter increasing in 2020. There is also a large variation across urban types amongst Eastern Europe. Emissions are clearly the highest in cities and are also significantly higher for residents of towns than those from rural areas.

### Urban differences and SDA

The results so far highlight general trends in emissions when grouped by location within Europe. This notwithstanding, it is evident from Figure 1 and the size of the error bars in Figure 2 that significant variation exists between countries. To extract more general trends, and any evidence of convergence/divergence of footprints by urban type, subsequent analysis uses the ratios between urban densities, instead of absolute values. It also focuses on the difference between city and rural residents only, since this provides a more robust distinction in urban morphology, whereas the town and suburbs classification captures, for example, areas adjacent to large cities and regional towns.

Figure 3A shows the ratio between urban and rural residents' emissions across time. A value greater than 1 indicates that per capita emissions are higher in cities than in rural areas. The average value for the whole of Europe is in red. For completeness, the average values using the countries that had available data is included as a dashed line. As also indicated by the results in Figure 2A, the average emissions remain higher in cities across the time-period considered. In general, the mean values suggest a slight decline in the ratio between 2005 and 2010, with no further change until at least 2015. It is difficult to draw further conclusions from the data given the limited time series. Note that here the error bars represent the standard deviation, rather than the SEM or confidence interval, to demonstrate the spread of values. Taking the uncertainty as the SEM, and rounding to the nearest 0.05, the overall emission ratios would be 1.15 ± 0.05, 1.10 ± 0.05, 1.10 ± 0.05 for the years 2005-2015.

This general result, however, hides significant regional points of interest. Turning to the relatively richer countries of Western and Northern Europe denoted in blue, the emission ratio slightly decreased between 2005 and 2010 but was otherwise broadly static at or slightly below 1. Considering the 8 countries with full data between 1999 and 2015 gives values of 0.95 ± 0.05 in 1999 and 0.90 ± 0.05 in 2015, respectively. However, on the country level, significant changes are observed. The United Kingdom and Belgium have seen significant decreasing trends in the emission ratio (SI). The same was also seen for Norway and the Netherlands, but these countries could not be included in the time series due to missing data for certain years. Whilst always exhibiting lower emissions in cities, France shows the opposite picture, with the emissions ratio increasing rapidly between 1999 and 2015. Additionally, Austria is also an outlier in having higher emissions in cities between 1999 and 2010, although the emission ratio thereafter became rather similar.

Southern Europe - highlighted in black - shows a slow decrease in the emission ratio since 1999. Although emissions remain higher in cities than rural areas, the ratio changes from 1.10 ± 0.05 in 2005 to 1.05 ± 0.05 in 2020. Portugal has seen a notable decrease in the emissions ratio, especially between 1994 and 2005 (the emissions ratio was 1.75 in 1994), although this was not included in the graph due to limited data from other countries. This is against a backdrop of declining overall emissions, suggesting that emissions are falling slightly quicker in urban than rural areas. Similarly, the green curve in Figure 3A also demonstrates a decrease in the ratio of emissions between urban and rural residents in Eastern Europe between 2005 and 2010, but little overall change otherwise. The overall values decreased from 1.30 ± 0.07 to 1.20 ± 0.05 between 2005 and 2010, with the same value seen in 2015 and 2020 when rounding to the nearest 0.05.

SDA was used to understand any changes in the factors contributing to the emissions ratios. Figure 3B-D show the results of the four-factor structural decomposition (with the emission factors being equivalent in all cases) analysis for Western, Southern and Eastern Europe, respectively. Results are expressed using box plots with the effects of household size given in green. This was included to attempt to separate true expenditure changes on a per capita basis from those associated with changes in the number of people living in the households, and how these factors vary over time between urban and rural areas. The corresponding factor for expenditure is in blue, with that for the consumption structure in turn shown in red. The emission ratio is given as a solid black line. Whiskers in the box plots give the maximum and minimum range of recorded values, with the box edges defining the interquartile range. The central line and black diamond record the positions of the median and mean, respectively. A full breakdown of results from the SDA is given in Supplementary Tables 4-6.

Several aspects are notable from considering the results for Western Europe in Figure 3B. There is some evidence for competing factors beneath the broadly static emission ratio. The analysis suggests that relative expenditure has decreased since 1999 for residents in cities (particularly between 2005 and 2010) and since 2010 rural households have on average had higher overall expenditure. On the other hand, the mean values for the structure of consumption increased between 1999 and 2005 and was thereafter static, with a value of 0.90 ± 0.05 in 2015. Note that this includes expenditure on real and imputed rent, which tend to be higher in urban areas. Relative differences in household occupancy have exhibited little notable change and are consistently above 1. Thus, the slight trends in overall expenditure and consumption structure work against each other and lead to a slight lowering of household emissions in cities than rural areas.

Different drivers are apparent in the decomposition for Southern Europe. From 2005 to 2015, the index for overall expenditure decreased from 1.25 ± 0.06 to 1.15 ± 0.05. However, in Greece the total expenditure index has been increasing from 2005, and without this a more pronounced decrease in the average would be seen. A decrease has also been seen in the index for consumption structure. Whilst this has always been less than 1, it further decreased between 2005 and 2020 from 0.90 ± 0.05 to 0.85 ± 0.05. Conversely, since 2005 the household size index, shown in green, has increased. Thus, the overall higher emissions in cities than rural areas for Southern Europe arises from higher expenditure alongside smaller household sizes (which suggests a larger expenditure difference on a per capita basis); the gradual decrease in the emissions ratio results from the contrasting changes in household size and consumption structure, alongside the decrease in the expenditure index between 2010 and 2015.

The results for Eastern Europe are finally shown in Figure 3D. An initial feature of the decomposition is the differences in the mean and median total expenditure index. Whilst all countries have higher expenditure in cities, for several countries, such as Bulgaria, Latvia and Lithuania, this difference is especially large for some years. There has, however, been a decrease in this value from 1.30 ± 0.07 in 2010 to 1.20 ± 0.06 in 2020. On the other hand, the consumption structure index results, shown in red, are on average below 1. Indeed, there are only a few values greater than 1. There was a change in this metric between 2005 and 2010 from 0.90 ± 0.05 to 0.85 ± 0.05, after which it has remained static. The household size index in green increased slightly from 1.10 ± 0.05 to 1.15 ± 0.05 between 2010 and 2020. Summarising, the significantly higher per capita emissions found in urban areas are caused by higher expenditures, on average, alongside smaller household sizes, which are only partially counteracted by the structure of consumption. The driving force for the decrease in the emissions ratio are changes in consumption structure of city households relative to those in rural areas between 2005 and 2010, with decreasing differences in overall expenditure also seen since 2010 being offset by increases in household size.

The analysis could also be performed by weighting country results by population. Supplementary Figure 2 shows an equivalent figure with both the emissions and decomposition indices being weighted by population. In this way, the emission ratio is seen to drop for all of Europe, as well as the countries of Southern and Eastern Europe; the emission ratio for Western Europe remains below one and decreased between 2010 and 2015.

The curves in Figure 3A included nearly all areas of household expenditure. But the ratio of emissions and particularly the differences in consumption structure could be affected by relative spending on lower emission service sectors and differences in housing costs. That is, analysing the drivers may not give a true picture since differences between higher emission sectors may be hidden by those in other categories that reduce the overall average emission intensity. Moreover, arguments for density being an effective strategy for emission mitigation largely focus on the opportunities for direct or indirect resource sharing, for instance through better public transport networks or more communal heating. It is therefore of interest to only focus on transport and household energy use to try to isolate any positive association with urban living.

The same analysis as presented in Figure 3 was therefore repeated considering only the sectors of transport and household energy and is shown in Figure 4. Figure 4A shows the time series of per capita emission ratio between city and rural residents, again grouped by geographical area. As before, the results are shown for all analysed countries in red, as well as Western, Southern, and Eastern Europe in blue, black, and green, respectively. The same general trends as Figure 3A are repeated when looking at only transport and household energy. When all countries are considered together, the emissions ratio decreases between 2005 and 2015 from 1.10 ± 0.06 to 1.05 ± 0.05. Again, the increase between 1999 and 2005 is caused by the expansion of countries and is not considered a real effect. The blue curve for Western Europe is consistently less than 1, indicating that rural residents have higher emissions on transport and energy than those living in cities. The average ratio varies between 0.85 and 0.90 throughout all years. The black and green curves for Southern and Eastern Europe, however, show decreasing trends. For Southern Europe, this change has occurred since 2010 (from 1.05 ± 0.05 to 1.00 ± 0.05 in 2020). For Eastern Europe, a more pronounced decrease has taken place, with values of 1.3 ± 0.1 and 1.15 ± 0.08 in 2005 and 2020, respectively. Again, a full breakdown of results from the SDA is given in Supplementary Tables 7-9.

Figures 4B-D show the results of the SDA for the transport and household energy sectors, for Western, Southern and Eastern Europe, respectively. As in Figure 3, the black curve shows the overall emission ratio. Box plots showing the distribution of the indices for expenditure, consumption structure and household size can be seen in blue, red, and green, respectively. Figure 4B first shows the results for Western Europe. Although, the emission ratio does not change significantly, the decomposition highlights that between 1999 and 2015, the overall expenditure ratio for travel and household energy was decreasing. Whilst always less than 1, indicating that rural residents spend more on these sectors than city residents, it further decreased from 0.90 ± 0.05 in 2005 to 0.75 ± 0.05 in 2015. However, that a reduction in the emissions ratio is not seen is a result of an increase in the index for consumption structure. Between 1999 and 2015 this increased from 0.85 ± 0.06 to 1.00 ± 0.07. In 2015, city households in these countries on average emitted the same carbon per euro spent on transport and energy as rural households.

These trends are not seen when looking at Southern Europe, the results of which are given in Figure 4C. The expenditure index was around 1.1 across all years, whilst the household size index increased, meaning that households in cities become smaller relative to those in rural areas. However, between 2005 and 2020 the index for consumption structure decreased from 0.95 ± 0.05 to 0.85 ± 0.05. Considering this, the decrease seen in the emission ratio per capita is being driven by changes in consumption structure.

Figure 4D shows the results for the countries of Eastern and North-Eastern Europe. Here, the results are similar to Figure 3. The results of the SDA suggest that the observed decrease is being driven by changes in total expenditure. First, the index of total expenditure shows a declining trend between 2005 and 2020 from 1.20 ± 0.07 to 1.10 ± 0.07. On the other hand, the consumption structure index was consistently around 0.95. No significant change in the household size index is seen between 2005 and 2020.

Supplementary Figure 3 provides the same information as Figure 4 but with the results weighted by population. Here, a decrease is again seen when all of Europe is considered together (with an emissions ratio consistently below 1) as well as for Eastern Europe. The decrease for Southern Europe is more pronounced when weighting by population.

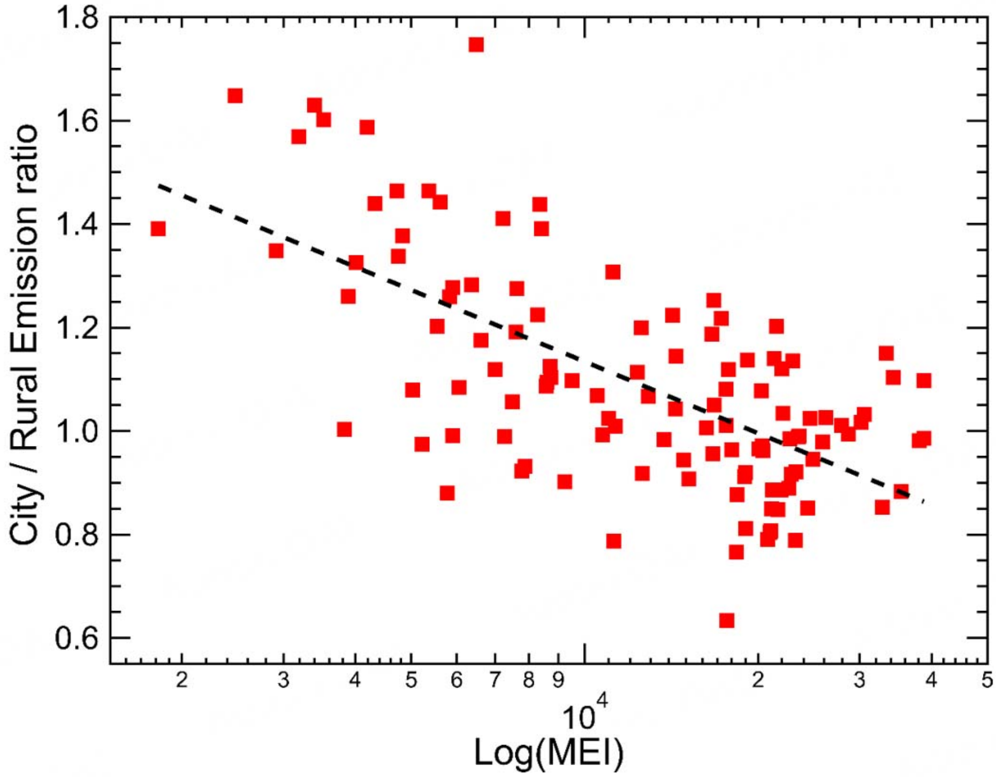


**Figure 5.** Graph showing the ratio of emissions between city and rural residents against national median equivalised income (in 2015 prices) for all national data available between 1994 and 2020.

## The link to prosperity

Finally, we consider the apparent differences across the regions of Europe may reflect differences in living conditions using the MEI as a proxy. The emissions ratios for all countries across all available years was plotted against the logarithm of MEI at the national level, as shown in Figure 5. The graph shows that, although the data is scattered, higher emission ratios are associated with lower MEI values. Considering, the semi-log graph, this was tested quantitatively by fitting Equation (1) to the data:

$$\text{Emissions ratio} = a + b\log(\text{MEI}) \quad (1)$$

A curve of the fitted relationship is shown in black showing an apparent weak negative correlation (the $r^2$ value of the linearised data was 0.4). MEI can be taken as a measure of disposable income, and all values are converted into 2015 euros. This implies that as the MEI of the country increases, there is first a quicker decrease in the emission ratio, after which it levels out as income further increases. This does not imply a causal link but rather reflects a general phenomenon of decreasing differences in emissions between cities and rural residents as incomes rise.

This comparison was further tested through mixed effects modelling, using random intercepts between countries and three explanatory variables (Ln(MEI), year, and Region as a dummy variable). The results are detailed and elaborated upon in the Supplementary Tables 10-14 and suggest that MEI alone offers the best explanation of the data available. This was deduced from comparing the respective Akaike information criterion (AIC) as well as the Bayesian information Criterion (BIC) from the models. Nevertheless, the modelling results also indicate that significant variance remains uncaptured, implying that additional unspecified factors are also important in explaining the ratio of emissions between urban and rural residents.

## DISCUSSION

This paper was set to advance our knowledge on how consumption-based emissions have developed over time across the urban-rural axis in Europe, and what have been the key drivers of that development. To reach this goal we conducted a time series analysis for the years 1994-2020 for 29 European countries. SDA analysed changes in the drivers of emission, with a particular focus on those explaining the relative changes across the urban-rural continuum. The research questions asked were:

1. How have personal carbon footprints developed for urban and rural residents across different regions of Europe?

2. What drivers of any (relative) changes can be elucidated from the data?

The results show distinct patterns across different regions of the continent. Whilst in richer Northern and Western Europe per capita emissions are generally lower in cities compared to rural areas, this is mostly associated with, on average, a lowering or reversing of expenditure disparities and any resource efficiency linked to urban-based lifestyles appears to be decreasing, at least when considering only energy and transport. On the other hand, in Southern Europe emissions are typically higher in cities, but the difference is slowly decreasing due to a relative decrease in the emission intensity of the consumption structure. The largest differences are seen with the countries of Eastern and North-Eastern Europe most associated with post-2000 EU expansion. Here, emissions and expenditure are consistently higher in cities than rural areas. However, these differences appear to be slowly converging as a result of reducing expenditure differences and slowly increasing emissions in rural areas.

One clear development pattern was a decreasing difference in emissions between cities and rural residents along with increasing MEI. Establishing reasons for this would require further analysis. One possible example could, for instance, relate to increasing car-ownership as income increases, and saturation of car-ownership in rural areas. Car-ownership increases the possibility of getting a higher paying job, particularly if one lives in rural areas[38-40]. At the same time, car-ownership increases personal carbon footprint significantly, especially if distance to work and services is long. There is also prior evidence of the income effect being particularly strong between low- and middle-income groups, but that the income elasticity of car ownership declines towards higher income groups beyond the point after which income does not hinder from owning[41,42].

Generally, only a few prior studies have focused on the development of consumption-based emissions over time and changes across the urban-rural axis. Among these, Wang *et al.* and Zhou *et al.* conclude that urban emissions are higher than rural in China, and generally rise alongside increasing urbanisation following rising incomes[26,27]. However, Zhou *et al.* find a saturation point and suggest that in highly urbanized areas, urban efficiency benefits play a role to mitigate emissions. Their results do not show convergence, although Zhou *et al.* cover a time-period from 2014 to 2020 and Wang *et al.* from 2002 to 2012[26,27]. However, a global analysis by Yuan *et al.* shows, similarly to our findings, that rural emissions are slowly converging with high urban emissions, particularly in the US and Europe[43]. A hypothesis could be drawn in which urban emissions first increase rapidly along with rising incomes, and lead to a relatively large gap between urban and rural footprints (such as discussed in Wiedenhofer *et al.* 2017)[44], with later convergence in incomes, and technological development narrowing leading to a decline in the urban-rural footprint gap. One factor behind the changes we observed might also be changes in the life course status of the residents of certain types of areas. The life course situation has been shown to play a role[11], and demography changes unequally in urban and in rural areas, with the latter ageing faster as younger people move to urban regions. Without data restrictions hindering us from looking at this, it could have been an interesting additional perspective to the SDA.

## Study limitations

The study attempts to use a consistent approach across an almost 30-year time-period. As such, we focused on using EEIO and HBS, as data is available in a consistent time series. However, this comes with well-documented limitations. The definition of degree of urbanisation follows the Eurostat definition and was specifically designed to ensure stability over time. However, issues associated with comparability in longitudinal studies are to some degree inevitable. To maximise comparability, the decision was taken to only focus on the differences between extremes (cities and rural areas) as well as looking at the ratio of emissions in the analysis. Applying EEIO assumes a linearity between consumption and emissions that may not fully reflect reality, as well as requiring products to be aggregated into a finite number of categories. Where possible and appropriate, the pure EEIO has been supplemented with additional data to improve the accuracy of the calculations. Moreover, whilst HBS are collected according to consistent methodologies, we can't easily deal with changes to this that have occurred over time. Sample sizes and temporal windows used by statistical agencies are relatively small, and this could be another form of error. To some extent, these factors are mitigated by considering the ratio between emissions rather than absolute values, as this allows data to be compared across different regions of Europe. It also reduced errors or inconsistencies so long as they are applied equally across urban densities. But certain types of expenditure or emissions may not be easily captured by the HBSs or by our model. Here, one example to consider is waste. Although for most countries such emissions were not significant, for several countries (for example, Denmark, Germany, Finland, Austria) they led to extremely large emissions in one or several years (typically due to extremely large emission intensities) and were removed to prevent potential biases in the results. For instance, for Finnish city residents, the share of emissions from waste increased from around 5% or less in prior years to 39% in 2015. This high variability between years is suggestive of an error, especially given waste emissions averaged around 4.5% of total emissions outside these countries. It was therefore decided that the safest solution that maintained a consistent methodology across all countries was to remove the waste emissions. Issues to do with the allocation of expenditure within the HBS could also lead to emissions not being estimated correctly. A well-known example of this is in the allocation of emissions from district heating, which for several countries may not be fully captured by the HBS (since they are embedded in other household costs). This could lead to emissions in cities being underestimated. In the future, this could be improved upon by utilising other sources of data such as additional bottom-up surveys, but this would have been challenging in the present case due to the need for consistent time-series data. Finally, some emissions will exist that are not recorded in the HBSs, either due to methodological problems or those arising through activities not associated with expenditure, but for which households are still the final consumer. One example here is self-sourced biomass. However, given the region (Europe) and time period (post 1994) these emissions are assumed to not be significant, though some evidence suggests that in the Northern part of Europe in less urbanized areas it might play a role[45].

We also have not considered the issues of uncertainty or sensitivity in full detail. Whilst we have included the variation between countries in each grouping and found these to be relatively stable (standard deviations are around 10% or lower of the emissions ratio), we have not performed full distributional analysis on the inputs used for our assessments. Work has generally supported uncertainty in greenhouse gas emissions derived from EEIO being lower than in other satellite accounts[46]. Nonetheless, this is itself a complicated research field and beyond the scope of the current work.

With regards to policy interventions, it should be noted that our method does not directly consider the effects of energy taxes since all prices are in basic prices. However, energy taxes could in principle cause changes in expenditure that would be tracked. But capturing whether this effect is present against other reasons for changes in expenditure across the cohorts would require more data and further analysis that is beyond the scope of this study. The same could be said of other specific policies that might be implemented but can't be directly isolated in the underlying data used for the model.

### Missing data

The time series of HBS include missing values. In some cases, entire countries are missing data, whilst in others it is not available for a particular urban type for a given year. One example is Eastern Europe prior to 2005. However, data is also missing elsewhere; many Western countries had no data for 2020. Efforts were made to draw comparisons that combined the most countries over the longest time periods, but this necessitated removing some data from the analysis for reasons not related to quality. For instance, Lithuania is not included in the analysis of Figure 2 and Supplementary Figure 1, since no data is available for towns and suburbs for 2005, the first year for which it had data. The countries that are included in each analysis are presented in Supplementary Tables 2 and 3.

Whilst this was done to increase comparability, any decision not to include a country is not a neutral act, particularly when full time series data is only partly missing, since missing data is not distributed randomly across our data sample. For Western and Northern Europe, Netherlands and Norway have been omitted from the regional comparison since they lacked data in 2005. However, on average these two countries had higher emissions compared to Europe overall and, at least for parts of the time series, in cities relative to rural areas. The effect is to lower the overall average emissions across all urban types in Figure 2 compared to if they were included, as well as to partly lower the ratio of city to rural emissions in some of the time series in Figure 3. This complicates the generalisation of conclusions that strictly should not be applied outside of the specific range of years and countries included in the analysis. The distribution in this study is not the same as for all of Europe (since Western Europe is under-represented).

An alternative would have been to include all countries and urban types where data was available. In the analysis of the emission ratios for Western Europe, doing so would have only caused a significant deviation to the results in 2010, when the emission ratio in the Netherlands was significantly above the average. Deviations in the absolute emissions between the consistent subset and when using all available data were typically around several percent. Such an approach would have been most valid if the sample size was large enough and the missing data was distributed randomly. However, it was decided to only emphasise results from the consistent subset of countries given that most data were missing from Western Europe and the sample size of countries was below 30 (and smaller for the regional groupings). Missing data could also have been interpolated, but this would have come with its own challenges and introduced additional sources of inaccuracy. The downside of performing the analysis in this way, as stated, is that the results in the strictest sense only apply for the countries included in the analysis. The dashed lines were added in the Figures 2-4 for completeness and to show the possible change in emissions across years where data was missing (except for the change between 1999 and 2005).

### Policy implications

The EU's policy for sustainable urban development emphasizes the integration of environmental, economic, social, and cultural aspects. However, research on the consumption-based carbon footprints highlights repeatedly that the gradual improvement of environmental efficiency doesn't offset the impact of economic growth and increasing consumption. Pursuing economic growth should not restrict the formulation and implementation of environmental regulations, such as increasing carbon pricing and removing subsidies for fossil fuels. Europe should hold on to its role as a world leader in climate and environmental policies. Using environmental footprints as indicators for environmental progress supports true integration of environmental and economic aspects. Indicators focusing purely on increasing efficiency are misleading if their interaction with economic growth is not considered. Environmental footprints can also support social development by revealing environmental inequality. For example, although rising income levels generally improve carbon intensity, air travel emissions concentrate on the highest income households, leading to disproportionately high personal carbon footprints[47]. Higher environmental taxes or fares on air travel would reduce both emissions and inequality.

## CONCLUSIONS

In this work, we have endeavoured to describe the relationship between emissions from urban and rural residents across Europe over time. This was done by linking publicly available HBS to EEIO-derived emission intensities and computing household footprints for different urban density types from 1994 to 2020. The results first indicate that any changes linked to urban density are typically weak relative to differences that exist between countries, whilst also showing a general narrowing in the distribution of emissions across nations over time, irrespective of urban type. Throughout the period from 1994 to 2020, emissions have also been consistently not conducive to remaining below either 1.5 or 2.0 °C, with the possible exception of rural residents in several Eastern European countries. This notwithstanding, distinct regional variations are also apparent, with drivers of these differences illuminated using SDA. Amongst countries that joined the EU during more recent waves of expansion, consisting of parts of central as well as Eastern and North-Eastern Europe, per capita emissions have been significantly higher in cities than rural areas across the considered time periods. As shown in Figure 2, average emissions, and expenditure of rural residents of these countries have remained mostly constant whilst those in cities have fallen overall.

Considering Southern Europe, emissions are decreasing across all urban types but remained on average slightly higher in cities than rural areas up to 2020. However, here the ratio of emissions between city and rural residents has been slowly decreasing over time. In this case, this is partly associated with a greater carbon efficiency in urban areas, and was seen when looking at all sectors, as well as transport and household energy. Finally, in Western Europe per capita emissions were found to be consistently lower amongst residents of cities, with no large-scale changes over time. This is also seen when only looking at household energy and transport. However, this itself arises from two competing phenomena, with expenditures tending to decrease in cities relative to rural areas between 2005 and 2010, whilst the structure of consumption becomes relatively more carbon intensive, particularly when only energy and transport are considered.

We also observe a weak negative relationship between the logarithm of national MEI and the emission ratio between city and rural residents. But understanding this apparent relationship, and establishing any causal link, would require more detailed analysis in which independent variables can be isolated from one another. All data used here was ensemble and a more detailed analysis using HBS microdata could form the basis for future research. Further analysis could also look in more detail at changes in the structure of consumption, and how this and overall emissions align with income, social outcomes, and perceived well-being across countries, regions, and the range of urban-rural typologies.

## DECLARATIONS

### Authors' contributions

Conceptualization, methodology, modelling, data analysis, visualisation, writing - original draft: Walke, P.
Methodology, validation, writing - review and Editing: Lylykangas, K.; Ottelin, J.; Heinonen, J. T.
Project administration: Lylykangas, K.

### Availability of data and materials

The data supporting the findings of this study are presented in this manuscript and Supplementary Materials.

### AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tools ChatGPT (version GPT-4o, released 2024-05-13) and GoogleGemini (2.5 Flash, released 2025-04-17) were used to aid the development of the code on which the

SDA analysis was based. AI was only used as an assistant and all code sections were significantly written by the authors. The tools did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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None.

## Conflicts of interest

Heinonen, J. T. and Ottelin, J. are the Editorial Board Members of the *Carbon Footprints* journal. Heinonen, J. T. is the Guest Editor of the Special Topic " Urban & Rural Carbon Footprints: Built Environments, Mobility, and Lifestyle Transitions " in the *Carbon Footprints*. They had no involvement in the review or editorial process of this manuscript, including but not limited to reviewer selection, evaluation, or the final decision, while the other authors have declared that they have no conflicts of interest.

## Ethical approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.



## Supplementary Materials

Supplementary Materials

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