A Top-Down Regional Assessment of Urban Greenhouse Gas Emissions in Europe

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Abstract This paper provides an account of urban greenhouse gas (GHG) emissions from 40 countries in Europe and examines covariates of emissions levels. We use a “top-down” analysis of emissions as spatially reported in the Emission Dataset for Global Atmospheric Research supplemented by Carbon Monitoring for Action from 1153 European cities larger than 50 000 population in 2000 (comprising >81 % of the total European urban population). Urban areas are defined spatially and demographically by the Global Rural Urban Mapping Project. We compare these results with “bottom-up” carbon accounting method results for cities in the region. Our results suggest that direct (Scopes 1 and 2) GHG emissions from urban areas range between 44 and 54 % of total anthropogenic emissions for the region. While individual urban GHG footprints vary from bottom-up studies, both the mean differences and the regional energy-related GHG emission share support previous findings. Correlation analysis indicates that the urban GHG emissions in Europe are mainly influenced by population size, density, and income and not by biophysical conditions. We argue that these data and methods of analysis are best used at the regional or higher scales.

Keywords Europe · Urban · Greenhouse gas emissions · Regional assessment · EDGAR

INTRODUCTION

Increasingly, human activities and their impacts are concentrating in the world's cities. While covering about 2.2 % (estimates ranging from 0.3 to 3 %) of terrestrial area, urban areas accommodate more than 50 % of the global population (United Nations 2010), generate more than 80 % of the global gross domestic product (GDP, Grubler and Fisk 2012) and will demand the lion's share of the US\$50 trillion needed for future infrastructure over the next 25 years (Urban Land Institute and Ernst & Young 2011). Because cities are central places of resource demand, economic activity, and building concentration—all of which will affect processes into the future—they are significant sites for climate change mitigation.

Local authorities influence urban energy consumption and emissions through, inter alia, energy, land use and transport planning, building codes, and waste management infrastructure. Greenhouse gas (GHG) emission inventories are imperative for improved energy and emission decision-making.

Researchers and municipalities have generated GHG emission accounts for a number of urban areas (Dhakal 2010; Kennedy et al. 2011), but comparability is limited due to methodological and data differences (Bader and Bleischwitz 2009). For example, inter-urban comparisons are plagued by differences in the definition of urban, the sources of emissions, the compounds estimated, and the techniques used in the estimations.

As a developed region, Europe is an important contributor of GHG emissions. By 2011 Europe (as defined by the UN, Table S1) contributed approximately 20 % of global carbon dioxide (CO₂) emissions from the consumption of energy (US EIA 2013). The cities in the region, with their unique structures and histories (Jenks et al. 1996; Guerois and Pumain 2008; Haase 2008; Nuissl

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et al. 2009; European Commission 2010) (see [Electronic Supplementary Material Section 1](#)) are important contributors of Europe's CO₂ emissions (IEA 2008). It is therefore not surprising that the GHG emissions from cities in Europe have been studied intensively. Indeed, European researchers are at the forefront of urban GHG emission accounting studies and have generated inventories for individual cities and large urban regions (see for example, Baldasano et al. 1999; European Commission 2003; Carney et al. 2009). These “bottom-up” studies stand out as important baselines for individual cities.

At the same time, few comprehensive assessments of urbanization and GHG emissions have been completed at the regional scale. This is mainly due to data constraints on collecting comparable information from a large number of cities. The most accepted regional accounting to date focuses on urban energy-related CO₂ emissions for four regions, including Europe (IEA 2008). This assessment finds that in 2006 activities in cities were responsible for 69 % of total primary energy demand in the European Union (EU).

As comparable urban GHG emission inventories are scarce, researchers have identified a wide range of GHG emission contributions from cities at the global scale; between 40 and 80 % of total (Satterthwaite 2008; Dodman 2009). The higher estimates often relate to energy-related CO₂ emissions while the lower estimates typically include a broader range of gases and sources, such as methane from agriculture. Improving our understanding of the contribution of cities to GHG accounts and ultimately to global climate change can better inform policy-making and mitigation efforts at regional and global scales.

A growing number of spatial databases are available for regional and global analyses of GHG emissions (de Sherbinin and Chen 2005). These data are sometimes used for analysis of individual or selected groups of cities (Butler et al. 2008; Butler and Lawrence 2009; Sovacool and Brown 2010; Duren and Miller 2012), but have yet to be used for “top-down” regional urban GHG emissions for Europe. Europe provides an interesting case region for such a top-down study, as there are several individual urban GHG studies completed with which to compare results. In this study, we use existing spatial databases to present a regional accounting of GHG emissions from urban areas in 40 European nations as of 2000, including 1153 cities and four dominant GHGs (CO₂, CH₄, N₂O, and SF₆). We explore the variation in GHG emissions across European urban areas using socioeconomic, urban form, and biophysical factors that are expected to influence GHG emissions levels. Finally, we compare these results to other studies performed for individual cities in Europe. Our findings confirm previous results, provide further insight into urban contributions to global environmental change, and open up new avenues for future analysis.

MATERIALS AND METHODS

This analysis employs multiple global spatially disaggregated datasets to quantify and explore the GHG releases from urban areas within Europe. We focus on emissions for the year 2000 to optimize data consistencies across and within the different datasets and to provide a baseline for future studies. We aggregate all spatial data to individual urban areas within our sample, as described below.

Defining Urban

Our interest is in viewing GHG emissions through an urban lens, which is an understudied perspective within the global climate change literature. Many options exist for designating comparable “urban” boundaries, ranging from narrow designations of high-density development to broader designations of metropolitan regions (Schneider et al. 2009). This study uses the Global Rural–Urban Mapping Project (GRUMP) to identify urban areas within Europe. GRUMP compiles a global database of more than 70 000 cities and towns worldwide, with spatial boundaries based largely on NOAA's Night-time lights dataset (Elvidge et al. 1997). The GRUMP boundaries correspond broadly to a metropolitan geography that includes both central cities and their suburbs, which we believe best captures the relevant scale for urban GHG accounting among the available options. GRUMP also includes gridded global population datasets for 1990 and 2000 that are keyed to national urban population estimates from the *World Urbanization Prospects* dataset (UN 2010). The use of GRUMP introduces uncertainties to the analysis (see [Electronic Supplementary Material Section 2](#)).

Using ArcGIS we overlaid the GRUMP's polygon file of urban spatial boundaries circa 2000 on the GRUMP population grids and used the Spatial Statistics tool to extract total population counts for 1990 and 2000 for each urban area. (All spatial datasets used here were projected to the same World Equidistant Conic map to allow interoperability.) We then calculated average annual population growth rates for the urban areas from 1990 to 2000. Last, we overlaid global land cover data provided by the GLC2000 project to estimate the total habitable land within the GRUMP urban boundaries, in order to calculate population densities. Here we define habitable land as including all land cover classes excepting water and ice.

For this study, we retain urban areas with more than 50 000 residents in 2000, which corresponds to 1153 urban areas within the 40 nations of Europe (see [Electronic Supplementary Material Section 3](#)) (United Nations 2010). The 50 000 resident threshold captures more than 83 % of the urban population within Europe, according to the United Nations (2010).

The Urban Emissions Inventory

We use the Emission Database for Global Atmospheric Research (EDGAR), Version 4.0 (European Commission Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL) 2009). EDGAR is a spatial downscaling product designed to be used by modeling groups involved with atmospheric chemistry, scenario studies, and policy assessments (Olivier et al. 1994, 1998). EDGAR includes emissions from a variety of sources at the aggregate level of at least 0.1° spatial resolution (representing about $10 \times 10 \text{ km}^2$ at the equator). Here we use the EDGAR global grids of estimated emissions in metric tons for the year 2000 for the four most prevalent GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and sulfur hexafluoride (SF_6). These four gasses are aggregated from 50 original anthropogenic activity-related sources to six categories: agriculture, energy (electricity and heating), industrial processes and product use, residential, transportation (including aviation), and waste (see [Electronic Supplementary Material Section 4, Table S2](#)). The EDGAR gridded data do not include emissions from large scale biomass burning (forest, grassland and other vegetation fires and decay of wetlands and peat lands), and as such, those emissions are not examined here.

Using ArcGIS, we overlaid the EDGAR emissions grids onto the GRUMP urban spatial boundaries. Given that the EDGAR gridded emissions are provided at a coarser resolution than the GRUMP urban boundary data, we first generated new gridded emissions layers at the smaller GRUMP resolution by dividing the emissions counts in each cell by 60. We then used the built-in Spatial Statistics tool to extract total emissions for each urban area for each gas and each source category. We next transformed the emissions estimates by urban area for each gas into carbon dioxide equivalents ($\text{CO}_2\text{-eq}$) using global warming potentials reported by the IPCC (2007), and summed the totals across the four major gases. The result is a dataset with estimated GHG emissions for the year 2000 for the six major source categories in $\text{CO}_2\text{-eq}$ for each GRUMP-designated urban area worldwide with more than 50 000 residents. While EDGAR emissions are estimated from 1970 to 2008, the lack of more recent GRUMP population or urban boundary data precludes our evaluation of previous and more recent EDGAR emissions estimates.

EDGAR provides details of how they develop and allocate each of the GHG gases spatially (Janssens-Haenhout et al. 2012).¹ EDGAR begins with national-level emissions estimates and then allocates the national emissions spatially within each country based upon a number of factors depending on the gas and the source category, including population, population density, infrastructure networks, land

use, energy, industrial production sites, etc. Given the variety of sources and quality of information, data inaccuracies and uncertainty are introduced. We acknowledge several concerns with using EDGAR for the study of urban emissions.

First, EDGAR represents modeled values rather than direct observations. The reliance on proxy variables such as population and population density² to spatially allocate emissions for some sectors where more detailed spatial information is not available (i.e., residential and waste) is problematic for urban analysis, as it assumes that each resident anywhere is responsible for the same amount of emissions. We expect that individual impacts vary by the efficiency and management of available urban transport and energy infrastructure, for example. Scholars have argued that residents living in dense settlements use lower amounts of transportation fuels capita⁻¹ than those living in less dense cities (Newman and Kenworthy 1989, 1999). Moreover, this relationship changes with development; in less developed regions, residents in urban areas have greater access to fuel consuming technologies than those living in rural areas. Thus, the comparison of urban–non-urban per capita energy use from the US tend to differ markedly from findings in Asia (Dhakal and Imura 2004; Brown et al. 2008). Given that the EDGAR development team allocates some emissions by population as a proxy, we are handicapped in our ability to examine urban-to-rural gradients for certain sources of emissions. Incorporating population and population density as conditions for allocating emissions also inherently implicates those variables as important in explaining variation in emissions across urban areas. At a result, reality is undoubtedly more complicated and the emissions map much more differentiated than the global EDGAR dataset can portray.

Second, EDGAR version 4.0 uses country-specific emission factors when estimating emissions for each sector and for each technology. While the addition of emission factors for different technologies provides more detailed information than using average sector emissions factors, local emissions factors would be more accurate than national-level factors for estimating emissions from individual cities.

Third, uncertainties for some compounds in EDGAR could be large. Uncertainty estimates for GHG emissions based upon the EDGAR Version 4.0 are not available. EDGAR uncertainty estimates for Version 2.0, based upon expert judgment, suggest uncertainties vary by source: total uncertainties for CO_2 are small (10 % or less), for CH_4 are medium (10–50 %), and for N_2O are large (50–100 %).³

¹ See http://edgar.jrc.ec.europa.eu/kml_files_intro.php.

² EDGAR uses Gridded Population of the World, Version 3 (GPWv3).

³ See <http://themasites.pbl.nl/en/themasites/edgar/documentation/uncertainties/index.html>.

For EDGAR version 3, uncertainties are in the order of 10 % for carbon dioxide, 30 % for methane, and 50 % for all other gases (van Amstel et al. 1999).

Fourth, GHG emissions are allocated to the expected point of release in EDGAR. The use of these data is limited to identifying direct emissions at a particular geographic location. Direct emissions include those controlled by the political entities that define the geographic area. In GHG protocol language, the study of direct emissions constitutes a Scope 1 analysis (WBCSD and WRI 2004). Activities in urban areas, however, create substantial indirect GHG emissions. For instance, the electricity and heat used in urban areas often is produced outside of urban boundaries. Including the GHG emissions from the production of electricity or other energy carriers used in urban areas, but produced outside of urban jurisdictions constitutes a Scope 2 analysis. Using solely a Scope 1 analysis ignores the important contribution of electricity and heat production GHG emissions to urban areas. Furthermore, a Scope 3 analysis would include all urban related GHG emissions, such as indirect emissions from “vicarious activities” such as agriculture and forestry clearing in rural areas that serve urban customers. Scope 3 analyses also includes GHG emissions related to transportation of vehicles not owned or controlled by the geographic entity, waste disposal activities not within the target area, and the GHG emissions embodied in the goods consumed within the urban areas (Schulz 2010). These indirect emissions can be significant. For example, a study of Denver found that indirect emissions including air travel, fuel processing and cement and food consumption increased the individual resident’s emissions by over 30 % (Ramaswami et al. 2008; see also, Hillman and Ramaswami 2010).

We argue that the EDGAR data, supplemented by other information, allows for analysis of urban emissions from Scopes 1 and 2 in accordance with the World Business Council for Sustainable Development and World Resources Institute accounting protocol (WBCSD and WRI 2004). First, as mentioned, the GRUMP urban boundaries are more inclusive of suburban and peri-urban activities than politically derived boundaries (Schneider et al. 2009), and thus already include some emissions from outside the immediate urban jurisdiction as desired for a Scope 3 analysis, such as from transportation and waste disposal. Second, we also include aviation and navigation related emissions from within the urban extent, which also help to create a more inclusive GHG emission inventory. Finally, we add to the EDGAR energy-related emissions those from the Carbon Monitoring for Action (CARMA) database to approximate a Scope 2 analysis (see [Electronic Supplementary Material Section 5](#)). CARMA is a global database of carbon dioxide emissions from over 63 000 power plants and 4000 power companies worldwide for the year 2000. We presume that

urban residents use much of the energy produced by power plants outside urban areas. We identify the power plants located outside of urban extents using the CARMA data and aggregate the CO₂ emissions from these power plants at a national-level. We then proportionately allocate the emissions from these power plants to urban areas according to their individual share of urban land area within the country. In this regard, we create a range of emissions for urban extents. The low end of the range (lower estimate) counts direct emissions from within urban extents that were extracted from EDGAR. The high end of the range (high estimate) includes CO₂ emissions from thermal power plants outside the urban extents. Separating the emissions from power plants in this manner avoids double counting of emissions.

There are limitations to this method. First, the high estimate over-estimates the amount of energy-related emissions used by cities, by allocating all CO₂ emissions from power plants in each country to urban areas. Second, the approach ignores the urban-to-urban transfer of electricity and its associated GHG emissions. For example, the GHG emissions from some small urban areas may be produced from power generation for larger cities or entire regions (such as Cottbus, Germany), but the emissions from these activities are allocated to the site of production. Third, the spatial area of an urban extent may or may not be the best mechanism by which to allocate non-local electricity emissions. Nevertheless, we believe this approach provides a plausible upper-bound estimate of urban GHG emissions from energy-related activities and that the resulting range of values better informs decision-making than would a single point estimate.

Examining Covariates of Urban GHG Releases

One advantage of our approach is in the generation of comparable GHG emissions estimates across all of the major urban areas within a region. We can use this top-down estimation to examine in more detail the patterns of GHG emissions within Europe across multiple sectors. Previous regional assessments focused on energy-related CO₂ from the EU countries only (IEA 2008).

A second advantage of our approach is the generation of comparable GHG emissions estimates for a large number of urban areas, with which we can explore how the estimates vary with respect to some key factors thought to influence urban GHG emissions. Comparative empirical research on the urban–environment interaction is quite limited. Most empirical studies of environmental degradation necessarily employ national-level data given limitations on urban-scale data. The best available previous research on the drivers of urban environmental degradation employed air pollution and transport energy use estimates

for 84 global cities as of the mid-1990s (Romero-Lankao et al. 2009). The study tested several possible explanations for variation in urban pollution, including variables from economic modernization theory such as population and affluence, from human ecology such as population, density, and local climate, and from the urban transitions literature such as population, availability of public transportation, and affluence (Romero-Lankao et al. 2009). These researchers found that variables from the economic modernization and human ecology perspectives best-explained variation in urban air pollution and energy use among the studied cities.

Here we use a similar approach to explore the variation in urban GHG emissions within Europe. We use a modified “STIRPAT” specification (York et al. 2003) of the multiple regression model as follows:

$$\ln(E) = a + b_1[\ln(P)] + b_2[\ln(A)] + b_3[\ln(D)] + b_4[\ln(R)] + b_5[\ln(C)] + d_c + e, \quad (1)$$

where E represents urban-scale CO₂-eq emissions; P is urban population; A is income; D is population density; R is recent population growth rate; and C is an indicator of local climate. Country-specific fixed effects (via indicator variables, d_c) are included to capture unobserved country-level variation, such as from industrial policies, sociocultural differences, or environmental sensibilities. The logged specification produces regression coefficients that indicate the elasticity of emissions to changes in the explanatory factor. Positive coefficients greater than 1 indicate a more than proportionate positive influence of the factor on emissions; positive coefficients less than 1 indicate a less than proportionate positive influence on emissions; with the opposite effect for negative coefficients.

We note that the model variables are interrelated (especially population, density, and growth rate) and that the model is likely to be underspecified. Important factors that might affect the variation in urban GHG emissions but that we have not modeled here include local policies and plans, the efficiency and management of energy and transportation infrastructures within cities, the environmental proclivities of urban residents, the age, educational and occupational distribution of residents, and the economic function of the city. For these reasons we argue that the analysis is exploratory in nature and aims to highlight covariates rather than causes of urban GHG releases.

Data for the model covariates were obtained from several sources, including GRUMP as explained above for population size, growth rate, and density. Income data are from the International Institute for Applied Systems Analysis (IIASA) downscaled spatial socioeconomic dataset. We use the GDP at market exchange rate (MER) per cell for the year 2000 in US\$1990 and use GRUMP grid population to calculate capita⁻¹ figures. For the economic data,

we used ArcGIS to extract the income for each urban area from the IIASA B1 scenario global income grid, which we interpret as the middle level economic future compared to the A2R and B2 scenarios.⁴ We acknowledge that the resolution on the income data is coarse and cannot represent a specific estimate of income for each urban area. Rather, the data represent a generalized affluence level, ranging from low to high. Despite the uncertainties, we argue that the IIASA data are the best available for generating income indicators for all of our sample cities, and that it was better to include this proxy for affluence than not to include an income indicator at all.

Last, our indicator for local climate was calculated as the sum of heating and cooling degree-days for the urban center using Climatic Research Unit at University of East Anglia⁵ point data for temperature and diurnal temperature ranges. Higher values represent a stronger energy demand either for heating, cooling, or both, which we expect to associate with higher urban emissions. We also tested latitude and heating degree-days by itself, with similar results as to the combined variable.

RESULTS

We describe our exploratory analyses including descriptive, statistical, and comparative results below.

Urban Share of European GHG Emissions

For 2000, the total GHG emissions from anthropogenic sources (excluding emissions from large biomass burning and aviation and navigation over oceans) in Europe were approximately 8320 million tons of CO₂-eq emissions, about 23 % of the global total (Table 1). At the same time, Europe houses approximately 12 % of the world’s population (United Nations 2005). The largest source of total European GHG emissions was for energy conversion (50.8 %), followed by transportation (14.9 %), residential (12.1 %), industry (11.2 %), agricultural (7.8 %), and waste (3.2 %).

Of the total European emissions, approximately 3730 million metric tons CO₂-eq emissions were released directly within European urban areas (low estimate),

⁴ Scenarios are designed to make projections of possible future climate change. The scenario families contain individual scenarios with common themes, but with different assumptions about future population and economic growth, land use and other driving forces. The resulting output from the scenario family is a range of future emission and impact levels. Among the three scenarios identified in this paper, the B1 scenario provides emissions and impacts between those of the A2R and B2 scenarios and is therefore considered to produce the medium levels of emissions and impact.

⁵ “Ten Minute Climatology” <http://www.cru.uea.ac.uk/cru/data/hrg/tmc/>.

Table 1 Global European total and European urban GHG emissions, by sector, 2000

Sector	Global total emissions		European total emissions		European urban emissions			Urban share of European total Percent
	Million metric tons CO ₂ -eq	Percent	Million metric tons CO ₂ -eq	Percent	Million metric tons CO ₂ -eq	Percent		
						Low	High	
Agriculture	5024	14.4	651	7.8	59	1.6	1.3	9.0
Energy	16 681	47.9	4225	50.8	2132	57.2	65.1	50.5
Energy (high estimate)					2981			70.5
Industry	3158	9.1	935	11.2	444	11.9	9.7	47.5
Residential	3346	9.6	1010	12.1	403	10.8	8.8	40.0
Transportation	5030	14.5	1240	14.9	587	15.7	12.8	47.4
Waste	1563	4.5	259	3.1	105	2.8	2.3	40.5
Total GHG emissions	34 802		8320		3730			44.8
Total GHG emissions (high estimate)					4579			55.0

Estimates for urban areas (those directly from within urban extents) and “high estimates” when emissions from thermal power plants are added to totals. Percent columns for global, European total emissions and European urban emission should add to 100. Urban share of total European estimates are the urban share for the region. For example, the 9.0 % of all agricultural GHG emissions from Europe are from within urban extent borders. The table suggests that urban areas are responsible for between 44.8 and 55.0 % of total European emissions

comprising 44.8 % of the European total. The largest contributions to European urban GHG emissions were from energy conversion (57.2 %), followed by transportation (15.7 %), industrial (11.9 %), and residential (10.8 %). Agricultural GHG emissions, as expected, were the smallest contributions of European urban GHG emissions (1.6 %). The re-allocation of CO₂ emissions from thermal power plants located outside urban extents to all urban extents in the region increased the emissions from European urban areas by 849 million tons CO₂-eq for 2000, bringing the urban energy share of European urban emissions to a high of 65.1 %. This high estimate increased the urban share of total European CO₂-eq emissions to 55.0 %.

Comparative per Capita Intensity of GHG Emissions Between Urban and Non-urban Areas

European urban areas average fewer CO₂-eq emissions capita⁻¹ than from non-urban areas (Table 2). In all sub-regions, the direct CO₂-eq emissions capita⁻¹ are lower in urban extents than non-urban areas, suggesting generally that urban areas are more carbon efficient than non-urban areas. In only one sub-region, Eastern Europe, the high estimates were approximately equal to or slightly greater than the non-urban lower estimate and the regional average. This may be related to the high levels of GHG production in the region, particularly for industry and energy conversion.

Largest Urban GHG Emitters and GHG Emitters per Capita

We aggregate the 50 largest urban GHG emitters and the 50 largest urban GHG capita⁻¹ emitters in the region and

Table 2 Comparative GHG emissions per capita, urban (range) with non-urban (range) and total sub-region, 2000

	GHG emissions (tons CO ₂ -eq capita ⁻¹)
Western	12.2
Urban	9.5–10.9
Non-urban	14.3–16.6
Northern	11.2
Urban	7.7–9.7
Non-urban	14.5–19.0
Eastern	12.5
Urban	10.2–12.5
Non-urban	12.4–15.0
Southern	8.4
Urban	5.7–7.8
Non-urban	9.3–12.5
Europe	11.4
Urban	8.7–10.7
Non-urban	12.4–15.3

Included are both high and low estimates for urban and non-urban areas within each sub-region. For example, the range in urban GHG emission capita⁻¹ for Western Europe are between 9.5 and 10.9 tons CO₂-eq capita⁻¹ while those for non-urban areas are between 14.3 and 16.6 tons CO₂-eq capita⁻¹

present the distribution of emissions and population by sub-region (Table 3). The 50 urban extents with the largest GHG emissions account for over 52 % of the urban emissions in Europe and approximately 36 % of the urban population. Most of the highest emitting urban areas are located in Eastern Europe (approximately 50 % of the top emitters) followed by Western (26 %), Southern (14 %), and Northern (10 %) Europe.

Table 3 GHG emissions (low estimate) in CO₂-eq and population from top urban GHG emitters, top urban GHG capita⁻¹ emitters, and all urban extents from the European sample, by sub-region, 2000

Sub-region	Number of urban extents	Total GHG emissions (CO ₂ -eq) (million tons)	Total population (millions)
Top 50 largest urban GHG emitters in Europe			
Western	13	596	49.0
Northern	5	294	34.2
Eastern	25	872	42.3
Southern	7	196	28.4
Total top 50 largest emitters	50	1958	153.8
Top 50 largest urban GHG capita ⁻¹ emitters in Europe			
Western	8	87	1.9
Northern	2	3	0.1
Eastern	33	568	13.4
Southern	7	38	0.7
Total top 50 largest emitters per capita	50	696	16
All European urban extents			
Europe	1153	3730	427.5

The 50 largest urban GHG capita⁻¹ emitters had emissions levels from 23.6 to 258.7 tons CO₂-eq capita⁻¹. These levels are extremely high capita⁻¹ and while this group housed approximately 3.7 % of the total European urban population, they created 18.7 % of total urban emissions for the region. The distribution of high urban GHG capita⁻¹ follows that of the highest emitters in aggregate, although there is greater concentration of the highest GHG capita⁻¹ emitters in Eastern Europe (66 %), followed by Western (16 %), Southern (14 %), and Northern (4 %) Europe.

Eighteen urban extents appear on both the largest GHG emitters and largest GHG emitter capita⁻¹ lists. If we add the GHG emissions (controlling for double counting), these 82 urban extents (7 % of the European sample) account for approximately 59 % of the region's urban GHG emissions in 2000.

Multiple Regression Results

Given the limitations of the model and the data as explained above, the exploratory regression results suggest likely influences on European urban GHG emissions (Table 4 for details). As expected, the strongest predictor of urban CO₂-eq emissions is urban population size. Holding all other variables constant, cities with larger populations produce more GHG emissions than cities with fewer residents. By itself, this finding is unremarkable. Of more interest is the size the coefficient (1.4) on population size, which indicates that urban emissions would increase by 1.4 % for every 1 % increase in population, on average. In Europe, where many cities may be battling a loss of

Table 4 Multiple regression results for all European urban extents, 2000

Variable	Total CO ₂ -eq emissions
Population	1.43*** (0.029)
Income	0.21*** (0.053)
Density	−0.653*** (0.058)
Growth rate	−3.758 (2.707)
Local climate	0.003 (0.007)
Constant	0.069 (0.341)
Indicator variables	Yes (40 categories)
Observations	1136
Model fit	$F(5,1091) = 917.25***$ RMSE = 0.7566
Adj- R^2	0.7983

Estimated with ordinary least squares regression; robust standard errors reported in parentheses; all variables natural log transformed

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$

population in coming years, we might infer that emissions would decrease by 1.4 % for every 1 % decrease in population. This “more than proportional” response in emissions to population, otherwise known as a population scaling effect (described in detail by Bettencourt et al. 2007), has been found by other scholars using the

STIRPAT regression specification but is subject to considerable debate (Romero-Lankao et al. 2009). Studies of German urban electricity consumption and U.S. urban CO₂ emissions found near-proportional impacts of population (i.e., coefficients close to 1) (Bettencourt et al. 2007; Fragkias et al. 2013). We are unsure the degree to which our observed scaling effect represents a real phenomenon, is an artifact of how EDGAR spatially allocated emissions within countries, or is an inflated effect due to omitted variable bias (where the effects of other correlated variables are subsumed by population size). Nevertheless, our finding suggests that further analysis should pay careful attention to possible population scaling effects on GHG emissions in Europe, rather than presume a linear, proportionate relationship. The form of the population-emissions relationship is particularly important for scholars forecasting emissions under different possible future growth scenarios.

After accounting for the dominant effect of population, our proxy variable for income capita⁻¹ is only modestly associated with emissions. The coefficient of 0.21 indicates that emissions might increase by 0.21 % for every 1 % increase in our income proxy. Incidentally, this income effect for European cities is weaker than what was previously found within Asia (Marcotullio et al. 2012), perhaps because the variation in income is narrower across Europe and at a higher level on average than across Asia. Further, we included mean-centered quadratic and cubic income terms to our base model to test for possible nonlinearities in the relationship between income and emissions as predicted by ecological modernization theory. We found minimal explanatory benefit from the additional terms and do not report those findings here.

The regression results indicate that cities with higher population densities produce fewer GHG emissions than cities with lower population densities, all else equal. We find that emissions may decrease by 0.6 % for every 1 % increase in urban population densities. The sign of these results are similar to those of Fragkias et al. (2013) for the U.S., although that study produced an elasticity of 0.17 %. Both results hint at a role for compact urban development in constraining the production of urban GHG emissions given a certain income level and population size. Nevertheless, the density variable is likely capturing other associated factors including the availability of public transport and the spatial distribution of jobs and housing within an urban area. Further analysis using more detailed urban form, urban transit, urban economy (whether the urban economy is predominately industrial or service oriented), and emissions metrics would be necessary to distinguish density from other effects in Europe. Last, the full model regression does not indicate a significant influence

of either recent population growth rates or local climate on urban GHG emissions in Europe (Table 4). We expect that these two factors remain important in influencing emissions in some locations but that other model variables, including the country-level indicator variables, together better explain variation in emissions at the regional scale.

Comparison of Individual Urban GHG Emissions and Regional GHG Emission Level with Bottom-Up Studies

As mentioned, over the past two decades scholars, practitioners and NGOs have produced a variety of “bottom-up” urban GHG emissions estimates (for a review see, Dhakal 2010). Recently, a selected number of these estimates have been published for comparison purposes (Hoorweg et al. 2011). We calculate the percentage difference that our nearest estimate differs from that estimate in the literature. We also calculate the absolute differences between the values for each city and find the mean differences in values at the regional scale. Table 5 demonstrates that of the 14 bottom-up studies considered comparable (city-to-city) with corresponding locations in our dataset, only 2 had estimates within our ranges. Our individual urban estimates differed from between −61.4 to 115.6 % from the values found in the literature (see [Electronic Supplementary Material Fig. S1](#)). The absolute differences between our estimates and those in the literature for “bottom-up” studies vary between −7.34 tons CO₂-eq per capita and 7.65 tons CO₂-eq per capita.

The difference between the studies’ findings decreases markedly when the emissions estimated for individual urban areas are aggregated to the regional scale. For example, the mean difference between studies is only −0.5 tons CO₂-eq capita⁻¹. The mean for the bottom-up estimates is 8.24 tons CO₂-eq capita⁻¹ while our mean low estimate is 7.44 and our mean high estimate is 8.01 tons CO₂-eq capita⁻¹.

It is important to remind the reader that many “bottom-up” estimates also vary significantly and indeed may not be comparable (Bader and Bleischwitz 2009). For example, estimates of CO₂-eq emissions per capita in London range from 4.4 metric tons (Sovacool and Brown 2010) to 6.2 tons (Greater London Authority 2010) to 9.6 tons (Kennedy et al. 2011) (or by over 100 %). Our comparison simply demonstrates differences and similarities between the different techniques, but *not* which method is more reliable. Further standardization of a protocol such as the recently announced ICLEI/C40/WRI GHG emissions accounting procedure will go a long way toward accurately calculating urban GHG emissions (ICLEI, C40 and World Resources Institute 2012).

Table 5 Comparison of values between top-down and bottom-up estimates for individual urban areas

City	Country	GHG emissions per capita (tons CO ₂ -eq/capita)				Percent difference	Actual difference
		Bottom-up estimate		Top-down estimate			
		Year	Value	Low	High		
Athens	Greece	2005	10.40	3.94	4.02	−61.4	−6.38
Geneva	Switzerland	2005	7.80	3.09	3.11	−60.2	−4.69
Stuttgart	Germany	2005	16.00	7.96	8.66	−45.9	−7.34
Porto	Portugal	2005	7.30	4.33	4.38	−40.0	−2.92
Frankfurt	Germany	2005	13.70	8.22	8.48	−38.1	−5.22
Hamburg	Germany	2005	9.70	6.58	6.65	−31.4	−3.05
Greater London	UK	2003	9.60	7.11	7.15	−25.5	−2.45
Madrid	Spain	2005	6.90	5.84	5.96	−13.6	−0.94
Prague	Czech Republic	2005	9.40	9.01	10.33	0.0	0.00
Ljubljana	Slovenia	2005	9.50	6.09	11.39	0.0	0.00
Barcelona	Spain	2006	4.20	4.87	4.91	15.9	0.67
Glasgow	UK	2004	8.80	11.59	11.73	31.6	2.79
Helsinki	Finland	2005	7.00	9.82	10.28	40.3	2.82
Paris	France	2005	5.20	7.64	7.65	46.9	2.44
Brussels	Belgium	2005	7.50	15.15	16.23	102.0	7.65
Stockholm	Sweden	2005	3.60	7.71	7.75	114.2	4.11
Oslo	Norway	2005	3.50	7.55	7.55	115.6	4.05

Source values for bottom-up studies from Hoorweg et al. (2011)

DISCUSSION

This analysis uses a new combination of datasets and through a new top-down analysis finds that urban areas in Europe contribute between 44.8 and 55.0 % of total GHG emissions. This account is lower than that of the IEA (2008) that concludes cities of the EU consume approximately 69 % of the region's primary energy and generate approximately 2600 million tons of energy-related CO₂ emissions (approximately 1000 million less than our CO₂-eq estimate). It is also arguably lower than that of Grubler et al. (2012), which estimates the urban share of final energy use globally is approximately 75 % and for Western and Eastern Europe is calculated to be 46 EJ.

Several factors explain the lower shares found in this study compared with others. First, other accounts typically focus only on CO₂ emissions and exclude N₂O and CH₄, which result predominantly from agricultural and land use change outside of cities. They also may not include all the sources examined in this study. Hence, our more comprehensive accounting of CO₂-eq results in higher absolute emissions levels and a lower share of European emissions from cities. For example, from our database, restricting the analysis to only CO₂ emissions finds urban Europe responsible for between 49.3 and 62.0 % of total CO₂ emissions from the region. Similarly, if we restrict the analysis to only

energy-related GHG emissions, the range we found is between 57.2 and 65.1 %. The high estimates of both these findings are close to the IEA (2008) result. Second, we follow the UNs definition of Europe, which includes many countries outside the EU especially Russia. Hence, the border definitions will explain much of the difference. Third, this study uses a large number of urban areas of various sizes. Most other studies concentrate on the largest cities, where data are available. Providing a larger number of different sized urban areas may result in different shares, as cities of different population size produce different GHG intensities. Finally, this study uses a base year of 2000, while other studies typically use different years.

At the urban-scale we find differences between the levels of emissions from European urban areas and those of our study (our individual urban estimates differed from between −61.4 to 115.6 % from those reported in the literature). We do not expect, however, the estimates from top-down analyses to be as reliable as those from bottom-up studies due to the resolution of the data used. That is, the data points for each cell in our analysis define emissions within 100 km² area. Therefore it is very difficult to pick up differences in, inter alia, infrastructure quality and management, fuel type and quality, and governance arrangements that are important factors in explaining variation in urban emissions levels (Bulkeley 2013).

The averages of emissions capita⁻¹ between bottom-up studies and this study are close, suggesting that findings between the two types of studies converge at the regional scale. That is, the spatial databases and top-down analysis may provide useful information at this scale. These results support the close findings between this study and the regional analysis performed for Europe previously. Importantly, our study indicates the need to examine a larger number of GHG compounds to get accurate assessments of GHG emissions from urban areas.

Moreover, this study confirms that a small number of larger cities make are responsible for most of the urban GHG emissions (Hoorweg et al. 2011). It also suggests that the highest capita⁻¹ emitters make up a smaller percentage of total regional emissions.

The differences in emissions capita⁻¹ between urban and non-urban areas suggest that cities—while important sources of GHG emissions—have lower intensities than non-urban spaces. This finding suggests, if anything, that urban areas are not the only locations for focusing reduction targets (Dodman 2009).

The study also confirms the notion that GHG emissions levels are influenced by multiple factors. Like all human–environment interaction studies, the results can broadly inform urban policies. As noted by others (Parshall et al. 2010), two types of studies on urban CO₂-eq emissions have been completed. There are those that inventory local emissions to directly support local policy objectives and then there are those that analyze a cross-section of localities to derive general relationships between energy use and patterns of urban development. The top-down type of analysis presented here may be more applicable for the second use. As such, this study could be useful for providing information at the regional and higher scales. The covariate analysis suggests two important aspects of European urban CO₂-eq emissions. First, emissions are largely related to population size, density, and wealth. While not attempting to oversell these points, this finding confirms the results of other studies (Kennedy et al. 2009). We do not find temperature to be important as a determinant of urban energy consumption and GHG emission levels, after controlling for other factors, which is counter to previous findings (Kennedy et al. 2009; Grubler et al. 2012). Contrary to other studies, we find supra-linear relationships between GHG emission and population size. As Fragkias et al. (2013) argue, our finding creates a paradox for those scholars arguing that cities are similar to organisms (Bettencourt et al. 2007; Bettencourt and West 2010). That is, within the biological metaphor, as organisms grow in size, they become more efficient (Kleiber's Law). Our analysis suggests the opposite. Yet, we point out (above) that our results must be taken with caution. Certainly more work is needed to identify how and under what conditions these various factors affect emissions levels.

Second, smaller refined scale analyses are needed to examine the influence of specific urban form, infrastructure, fuel use, and governance arrangements at the local levels. Our findings must be supplemented with the more specific work from individual case studies, particularly because of unique aspects of European urbanization, including stable growth rates and shrinking cities. There is also need for developing urban typologies that could apply to sets of cities across this and other regions. Moreover, additional methodological developments with coherent and harmonized life cycle based activity and emissions inventories would be desirable for the design, monitoring, and verification of fair and effective climate change mitigation strategies.

CONCLUSIONS

Carbon accounts for cities are critical to developing urban climate change mitigation strategies. Although a substantial amount of research has focused on individual cities, regional approaches have been limited and few studies have generated comparable results across cities for covariate analysis, leaving urban GHG emissions insufficiently understood. This exploratory study has demonstrated that top-down analysis at the regional scale confirms previous bottom-up studies and provides new areas for further study. For example, we confirm the significant (but lower than previously estimated) role of cities in total share of GHG emissions, the variation in GHG emissions among cities and the importance of the largest emitters. We also demonstrate the multiple influences on urban GHG emissions levels. The findings also do not confirm results other studies, including those that find temperature important to urban energy consumption and therefore GHG emissions and that increasing urban size (defined by population) does not bring economies of scale in regards to GHG emissions levels.

Given this analysis, we see potential for using EDGAR and other spatial datasets for the examination of emissions from a large sample of cities worldwide, well beyond the sample sizes typically garnered by other approaches. Additionally, the top-down analysis may be useful in developing forecasts of regional and global urban GHG emissions under different policy scenarios. Furthermore, more refined top-down studies can be geared to explore important planning and environmental management issues, such as the contribution of peri-urban agriculture and waste management activities to the GHG profile of cities. Typically, emissions inventories focus on carbon dioxide without accounting for other globally important gases such as CH₄ and N₂O. The top-down analysis with multiple GHGs provides a wider view of the opportunities available

for meaningful mitigation of GHG emissions at the regional and global scales, as well as for tracking the effectiveness of previously adopted policy and planning efforts.

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