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# The geography of global urban greenhouse gas emissions: An exploratory analysis

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# The geography of global urban greenhouse gas emissions: an exploratory analysis

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**Abstract** The purpose of this paper is to describe global urban greenhouse gas emissions by region and sector, examine the distribution of emissions through the urban-to-rural gradient, and identify covariates of emission levels for our baseline year, 2000. We use multiple existing spatial databases to identify urban extent, greenhouse gas emissions ($CO_2$, $N_2O$, $CH_4$ and $SF_6$) and covariates of emissions in a "top-down" analysis. The results indicate that urban activities are significant sources of total greenhouse gas emissions (36.8 and 48.6 % of total). The urban energy sector accounts for between 41.5 and 66.3 % of total energy emissions. Significant differences exist in the urban share of greenhouse gas emissions between developed and developing countries as well as among source sectors for geographic regions. The 50 largest urban emitting areas account for 38.8 % of all urban greenhouse gas emissions. We find that greenhouse gas emissions are significantly associated with population size, density, growth rates, and per capita income. Finally, comparison of our results to "bottom-up" estimates suggest that this research's data and techniques are best used at the regional and global scales.

## 1 Introduction

Decision makers need baseline data, analysis and monitoring of urban greenhouse gas emissions to verify the effectiveness of policy measures. For example, while urban planners take

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compact cities as axiomatic to sustainable cities (see for example, UN-Habitat 2011), questions remain as to how effective compact policies would be in addressing climate change. Urgency for urban climate change policy is driven by increasing concentration of population; growth of urban activities that produce greenhouse gas emissions (GHG) (Hoornweg et al. 2011a; Rosenzweig et al. 2011); and the long lasting legacy of urban investment decisions.

Despite these needs, urban GHG emissions are not well understood (Dhakal 2010). A recent estimate finds that cities are responsible for between 56 and 78 % of final energy use globally, with a central estimate of 76 % (Grubler et al. 2012), and that globally cities are responsible for approximately 71 % of total energy related $CO_2$ emissions (IEA 2008). The first estimate only considers energy use and not GHG emissions and the second estimate only evaluates $CO_2$ emissions. A fuller examination of emissions from additional GHGs and sectors would improve our understanding of cities' contribution to global climate change.

Numerous studies have estimated individual city GHGs (for summaries see, Hoornweg et al. 2011b; Kennedy et al. 2011). Typically, individual urban GHG accounts are produced by local governments, NGOs and other agencies (Bangkok Metropolitan Administration 2007; Bloomberg 2007). Most case studies focus on similar types of urban areas such as large cities (Kennedy et al. 2011; Butler et al. 2008; Brown et al. 2008), leaving few that estimate emissions from medium size and small centers where urbanization currently occurs most rapidly.

Internationally, few studies systematically estimate emissions from a large number of cities. The most comprehensive study compares 44 cities (Kennedy et al. 2011). Even within this study, however, discrepancies exist between GHG protocols applied to different urban areas. Methodological differences include variations in the geographic definition of cities or urban areas, the gases included, source activities and sectors considered, and the conversion factors used to make emission estimates. Therefore considerable uncertainties are introduced to comparisons and aggregation estimates of urban GHG emissions (Bader and Bleischwitz 2009). It should not be surprising that great variations exist amongst aggregate urban emissions estimates at the global scale, of between 40 and 80 % of total (Satterthwaite 2008). Additionally, few analyses examine covariates of urban GHG emission levels, which could be used to better understand the spatial distribution of emissions and the factors that might prove effective as levers for policy action. While some studies have compiled enough data to perform quantitative analysis (Kennedy et al. 2011; Kenworthy et al. 2000) others are largely qualitative (Sovacool and Brown 2010; Croci et al. 2011).

We contribute to this area of research by applying an urban lens to existing GHG emissions data at the global and regional scales. Using existing spatial data, we estimate the urban share of emissions for the four most important GHGs ($CO_2$, $CH_4$, $N_2O$ and $SF_6$) at each scale and calculate the importance of different sectors as urban GHG sources. We identify a group of the most substantial urban GHG emitters. We describe the emissions across an urban-to-rural gradient by region and globally and perform an analysis of covariates of emissions. Finally, we compare our "top-down" estimates with results from previous "bottom-up" studies. These findings are important in two different ways. First, they demonstrate the applicability and limitations of a "top-down" methodology for estimating the geographic distribution of urban GHG emissions. Second, we argue that our findings provide substantive insight into the role of urban activities in climate change.

## 2 Data and methods

Our data and methods are described briefly here. For further discussion of the data and methodology, we refer interested readers to Marcotullio et al. (2011), (2012) and to the online supplement for this article.

We use the Global Rural–Urban Mapping Project (GRUMP) dataset to identify urban areas and population. GRUMP provides both the geographic boundaries of urban areas, called urban extents, and the spatial distribution of national populations for 1990 and 2000 on global grids at 30 arc-seconds resolution. GRUMP derives the geographic boundaries of settlements from NOAA's Night-time lights dataset (Elvidge et al. 1997). The boundaries of settlements therefore are not based upon political jurisdiction. Population is distributed in GRUMP using an algorithm that operates on a country-by-country basis and uses UN national estimates for the year 2000 from the *World Urbanization Prospects* (Balk et al. 2004). We extract population for each urban extent using the spatial statistics function in ArcGIS.

For this study, we retain urban areas with more than 50,000 residents in 2000, which corresponds to 7,041 urban areas that include over 2.4 billion people or approximately 87 % of the total global urban population, when compared to UN figures (United Nations 2010). Thus, wherever we discuss our "urban" results we mean for the subset of urban areas with more than 50,000 residents; the many thousands of GRUMP urban extents with smaller populations are reported with our "non-urban" results.

We use global land cover data provided by the GLC2000 project to identify habitable land within urban areas, in order to calculate population densities. Here we define habitable land as including all land cover classes excepting water and ice. To approximate an urban-to-rural gradient we create 20, 40 and 80 km buffer zones around all urban extents. We include emissions from buffer zones that cross national borders, but count these emissions to the nation where the urban extent is located.

GHG emissions are identified using the Emissions Database for Global Atmospheric Research (EDGAR) (European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL), version 4, 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 data have been used in other studies of urban emissions levels (Butler and Lawrence 2009; Butler et al. 2008; Sarzynski 2012; Sovacool and Brown 2010).

The EDGAR data are reported by source categories on global grids at 0.1° resolution. For this analysis we use emissions in metric tons for the year 2000 for carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and sulfur hexafluoride ($SF_6$). We transform each compound into carbon dioxide equivalents using global warming potentials reported by the (IPCC 2007). The sum of GHGs is aggregated to six sources: agriculture, energy (electricity and heating), industrial processes and product use, residential, transportation, and waste. For transportation, we include road, non-road, aviation emissions crossing urban extents (mostly take-offs and landings) and navigation sources. We exclude emissions from large scale biomass burning (forest, grassland and other vegetation fires and decay of wetlands and peat lands), as such emissions data are not available within EDGAR, and aviation and navigation over oceans.

We acknowledge limitations in the use of EDGAR data for this exercise. Here we discuss several of the more important limitations but we elaborate further in the supplemental material.

One important aspect of EDGAR is that the GHG emissions are allocated to the expected point of release. Use of these data without supplement is limited to identifying direct emissions from a particular geographic location. Direct emissions include those emissions controlled by entities located within the geographic area. In GHG accounting parlance, direct emissions comprise a Scope 1 analysis (WBCSD and WRI 2004). Activities in urban areas, however, create substantial indirect GHG emissions. For example, 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 fuels used in urban areas, but produced outside of urban jurisdictions, comprises a Scope 2 analysis. A Scope 3 analysis includes all urban related GHG emissions including other indirect emissions from "vicarious activities" such as agriculture and forestry clearing in rural areas that serve urban customers, 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 average 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, the GRUMP urban boundaries are more inclusive of suburban and peri-urban activities than politically derived boundaries, 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 help to create a more inclusive GHG emission inventory.

Third, we supplement the EDGAR energy-related emissions with the Carbon Monitoring for Action (CARMA) database, which contains information on the carbon dioxide emissions of over 63,000 power plants and 4,000 power companies worldwide (see http://carma.org/) for the year 2000 to approximate a Scope 2 analysis. We presume that urban residents and businesses 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 $CO_2$ 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 estimates for urban extents. The low end of the range (lower estimate) counts emissions from only within urban extents. The high end of the range (high estimate) includes 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 supplemental approach. First, the high estimate will over-estimate the amount of energy-related emissions produced by cities, by allocating all 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, some small urban areas may provide power generation for larger cities (such as from Traralgon to Melbourne, Australia), but the emissions from these activities are allocated to the site of production. Third, the spatial area of an urban extent may not be the best mechanism by which to allocate non-local electricity emissions (although using area as opposed to population may account for some transmission losses over space).

We provide descriptive analyses of urban GHG emissions and examine the geographic distribution of emissions within 20, 40, and 80 km from urban extent boundaries to examine the urban-to-rural gradient of emissions. We aggregate our urban emissions estimates at the national, regional and developmental levels.[1]

The application of an urban lens to the global EDGAR dataset helps us understand, at least in a cursory fashion, the impact of urbanization on the spatial distribution of emissions worldwide. Yet, with more than 7,000 cities, our urban database is difficult to comprehend without further analysis.

[1] The country regional groupings can be found at http://unstats.un.org/unsd/methods/m49/m49regin.htm. For establishing development status in 2000 we use the United Nation Development Program's *Human Development Report* (2002). Developing countries are typically, but not always, defined by their low national gross domestic product levels. Developed countries are those of high gross domestic product levels. In 2000, there were 123 countries or areas designated as developing.

We found it instructive to explore the influence of possible covariates on urban emissions using multiple regression analysis. The analysis is purely exploratory; it helps us to see broad-brush relationships between estimated emissions and variables that may influence emissions and to identify urban areas where our emissions estimates deviate notably from expectations.

Here, we model GHG emissions at the urban scale as a function of population size, density, growth rates (1990–2000), per capita income, and local climate. The regressors were derived using publicly accessible and best available global spatial datasets. Population size, density, and growth rates were estimated using the GRUMP population distribution dataset as described above. Per capita gross domestic product (GDP) estimates were extracted for each urban centroid from the Greenhouse Gas Initiative database produced by the International Institute for Applied Systems Analysis (IIASA), under the B1 scenario for 2000. The IIASA data are only available at a coarse spatial resolution and thus our "urban" estimates are illustrative of economic development status and are not precisely estimated for each urban area. Local climate was estimated using historic average temperature data (1961–1990) from Climatic Research Unit (CRU), "Ten minute climatology," University of East Anglia (New et al. 2002), which were converted into heating and cooling degree days (HDD and CDD) and aggregated to provide a general indicator of the heating and cooling demands required in a local area.

Although the model derives from the basic IPAT and Kaya Identity formulations, we use the STIRPAT modifications commonly used in previous research in which the relationship of model variables are transformed by the natural logarithm to account for their multiplicative effect on the dependent variable (Hoffert et al. 1998; Waggoner and Ausubel 2002; York et al. 2003; Dietz and Rosa 1997). The regression model is likely to be underspecified; a city's age structure, urban form, quality of infrastructure and local environmental policies, for instance, might also account for variation in their emissions. At the least, we include country-level indicator variables in the model to account for unobserved factors relating to a country's socioeconomic characteristics and policy choices. A more detailed description of the regression model specification and variable construction is provided elsewhere (Sarzynski 2012).

## 3 Results

### 3.1 Urban share of global GHG emissions

Our analysis finds that for the year 2000, total anthropogenic GHG emissions, excluding emissions from large scale biomass burning and aviation and navigation emissions released over oceans, were approximately 34.8 billion metric tons $CO_2$-eq. Urban areas (those over 50,000 population) account for 36.8 to 48.6 % of total emissions or between 12.8 and 16.9 billion tons $CO_2$-eq. (Tables 1 & SI.1 and Figure SI.1).

Within regions, African urban GHG emission shares are lowest ranging from 21 % to 30 % of all African GHG emissions and North American urban GHG emission shares are highest ranging from 49 % to 73 % of all North American GHG emissions. Amongst developing countries, urban GHG emissions range from approximately 26–33 % of total emissions. In the developed world, urban GHG emissions range from approximately 47–63 % of total (see also Table SI.2, Figure SI.2).

### 3.2 Share of urban GHG emissions by source

The energy conversion sector comprises the largest source of urban GHG emissions, ranging from 54 % to 65 % of total urban GHG emissions (Table 2). Agricultural

**Table 1** Percent urban share of sector GHG emissions, by region, 2000

| Source | Africa | Asia | Latin America & Caribbean | Europe | North America | Oceania | Global |
|---|---|---|---|---|---|---|---|
| Agriculture | 2.4 | 6.0 | 2.2 | 9.0 | 5.0 | 4.9 | 5.3 |
| Energy (low) | 31.7 | 38.1 | 35.5 | 50.5 | 41.4 | 35.3 | 41.5 |
| Energy (high) | 50.5 | 55.0 | 49.4 | 70.5 | 87.3 | 76.5 | 66.3 |
| Industry | 40.5 | 30.4 | 33.3 | 47.5 | 50.9 | 25.4 | 38.1 |
| Residential | 14.5 | 24.7 | 27.1 | 40.0 | 60.3 | 33.3 | 36.9 |
| Transportation | 30.4 | 34.3 | 38.9 | 47.3 | 68.4 | 56.3 | 50.9 |
| Waste | 18.7 | 32.6 | 40.4 | 40.5 | 64.1 | 50.9 | 38.8 |
| All urban (low) | 21.4 | 29.8 | 24.8 | 44.8 | 49.2 | 30.3 | 36.8 |
| All urban (high) | 29.5 | 37.9 | 29.3 | 55.0 | 72.8 | 50.2 | 48.6 |

"Energy (low)" includes only the energy GHG emissions from within urban extents. "Energy (high)" includes the energy GHG emissions within urban extents and the GHG emissions from thermal power plants outside urban extents apportioned by national share of the urban area size. "Global" includes all anthropogenic GHG emissions excluding large biomass burning and aviation and navigation GHG emissions over oceans. "All urban (low)" is the share of all urban GHG emissions for the region, using the "Energy (low)" estimate. "All urban (high)" is the share of all urban GHG emissions for the region using the "Energy (high)" estimate. For example, in Africa the urban agricultural share of all regional agricultural GHG emissions is 2.4 %. At the global scale, the urban agricultural share of global agricultural GHG emissions is 5.3 %

activities comprise the smallest source with approximately 2 % of total urban GHG emissions. Transportation accounts for 15–20 % of total urban GHG emissions, with road transportation responsible for over 90 % of urban transport emissions (Table SI.3).

Significant differences exist in source sectors between developing and developed countries. In developing countries, energy conversion accounts for between 61 and 70 % of all urban GHG emissions, while in the developed world the energy industry produces between 50 and 63 % of urban emissions. Transportation accounts for approximately 11 % of all urban GHG emissions in the developing world, while accounting for almost 25 % in the developed world's cities. Similarly, residential GHG emissions in urban areas of the developed world (11 % of total) are almost twice as important as those of the developing world (6 % of total). Agricultural, industrial and waste urban GHG emissions are larger in share in the developing world (4 %, 10 % and 7 %) than in the developed world (1 %, 9 % and 3 %). (Included in the supplement is a breakdown of urban GHG gases by source and region).

### 3.3 Comparative per capita intensity of GHG emissions between urban and non-urban areas

GHG emissions from the world's cities average between 5.2 tons $CO_2$-eq. per capita (low estimate) and 6.9 tons $CO_2$-eq. per capita (high estimate), while global non-urban emissions average from 4.9 to 6.1 tons $CO_2$-eq. per capita. The range of urban emissions per capita is lower than non-urban emissions per capita in all regions (Table SI.4, Figure SI.3) excepting Africa and Asia, where the ranges overlap. In Asia, the high estimate for urban centers is larger than the high estimate for non-urban locations and is also higher than the regional average. Arguably, Asian urban GHG per capita estimates should be higher than those in non-urban areas, as much of the region is developing and developing world cities are centers of technological adoption and infrastructure. Hence automobiles, for example, are largely concentrated within urban areas, which increase urban per-capita emissions. This trend is less important in the developed world, where automobile ownership is more ubiquitous.

**Table 2** Percent urban share of regional GHG emissions, by region, 2000

| Source | Africa | | Asia | | Latin America & Caribbean | | Europe | | North America | | Oceania | | All urban extents | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High |
| Agriculture | 3.15 | 2.28 | 3.52 | 2.77 | 2.92 | 2.47 | 1.57 | 1.28 | 0.57 | 0.38 | 4.24 | 2.56 | 2.07 | 1.57 |
| Energy | 63.88 | 73.83 | 61.35 | 69.61 | 45.88 | 54.15 | 57.16 | 65.10 | 43.20 | 61.59 | 56.09 | 73.46 | 54.13 | 65.31 |
| Industry | 8.32 | 6.03 | 11.37 | 8.94 | 10.45 | 8.86 | 11.89 | 9.69 | 4.85 | 3.28 | 4.02 | 2.43 | 9.41 | 7.11 |
| Residential | 5.28 | 3.83 | 7.64 | 6.00 | 6.39 | 5.42 | 10.82 | 8.81 | 12.05 | 8.15 | 3.53 | 2.14 | 9.64 | 7.29 |
| Transportation | 13.18 | 9.55 | 10.15 | 7.98 | 25.00 | 21.18 | 15.74 | 12.82 | 35.01 | 23.67 | 27.40 | 16.56 | 20.01 | 15.13 |
| Waste | 6.19 | 4.48 | 5.97 | 4.70 | 9.36 | 7.93 | 2.82 | 2.29 | 4.32 | 2.92 | 4.71 | 2.85 | 4.74 | 3.58 |

"Low" estimates include GHG emissions only from within urban extents. "High" estimates include GHG emissions from within urban extents and GHG emissions from thermal power plant emissions outside urban extents apportioned by national share of the urban area size. "All urban extents" include the emissions from the 7,041 urban extents in our global sample. For example, the share of urban agricultural GHG emissions among all African urban emissions is 3.15 % (low) and 2.28 % (high)

### 3.4 Largest urban GHG emitters and GHG emitters per capita

We aggregate the 50 largest urban GHG emitters and examine the distribution of emissions from these areas by region (Table 3). These 50 urban extents account for 38.8 % of global urban emissions while accounting for 19.8 % of the global urban population.

The majority of large GHG emitters are located within North America, with 21 urban extents accounting for 43.9 % of the emissions from this group (2,198 million tons CO2-eq.). Asia and Europe are each home to 12 urban extents on this list, with the Asian urban areas accounting for 31.2 % (1,565 million tons CO2-eq.) and European urban areas accounting for 19.9 % (995 million tons CO2-eq) of the group's GHG emissions. Latin America has four urban extents while Africa has one, producing 3.9 % and 1.1 % of the group's GHG emissions, respectively.

Compare these figures with emissions from the 50 largest urban per capita emitters. This group had emissions between 45.2 and 351.0 tons $CO_2$-eq. emissions per capita. While extremely high for per capita emissions, these entities account for only 6.0 % of global urban emissions and 0.4 % of the global urban population. The majority of high urban per capita emitters are in the Eastern portion of Europe (19), which produced 42.7 % of total emissions from this group. Several of the highest per capita emitters hail from Asia (13), comprising 26.2 % of emissions from group. North America was also home to several (13) of the highest urban per capita emitters, accounting for approximately 19.6 % of emissions in this group. Latin America, Africa and Oceania were home to very few of the largest emitters in aggregate or in per capita terms.

**Table 3** GHG emissions (low estimate) from the 50 top largest urban GHG emitters and 50 largest GHG emitters per capita, by region 2000

| 50 largest urban GHG emitters | | | |
|---|---|---|---|
| | | Total GHG | Total |
| Region | Number of urban extents | Emissions (CO2-eq) (million tons) | Population (millions) |
| Asia | 12 | 1,565 | 206 |
| Africa | 1 | 55 | 9 |
| Europe | 12 | 995 | 87 |
| Latin America & Caribbean | 4 | 195 | 53 |
| North America | 21 | 2,198 | 132 |
| Oceania | 0 | 0 | 0 |
| Top 50 largest emitters | 50 | 5,008 | 487 |
| 50 largest urban GHG per capita emitters | | | |
| Asia | 13 | 204 | 3.8 |
| Africa | 3 | 56 | 0.5 |
| Europe | 19 | 332 | 3.6 |
| Latin America & Caribbean | 0 | 0 | 0 |
| North America | 13 | 153 | 1.8 |
| Oceania | 2 | 33 | 0.1 |
| Top 50 largest emitters | 50 | 778 | 9.8 |
| All urban extents | 7,041 | 12,901 | 2,463.7 |

"All urban extents" includes all those urban extents in our database, which make up ~87 % of the global urban population (2,464 million population)

### 3.5 Distribution of GHG emissions: distance from urban extent boundary

Examining the distribution of GHG emissions by distance from urban extent reveals differences between developed and developing world regions (Table SI.5, Figure SI.4). In the developed world (especially Europe and North America) the largest sites of GHG emissions are in and around cities, with the exception of agricultural GHG emissions, which increase with distance from urban areas. On the other hand, in the developing world (especially Asia), peri-urban regions contribute the dominant share of emissions, with urban areas playing a secondary role for all sources except agriculture. For example, Asian GHG emissions from agriculture, energy, industry, residential, transportation and waste were all larger in the 20 km area directly outside urban extent boundaries. Thereafter, the percentage from each source drops off, with agriculture's share remaining lower but fairly evenly distributed throughout the other zones. For Africa, Latin America, and Oceania the non-urban areas beyond 80 km remain significant contributors to regional emissions, consistent with their less urbanized geography. Recall that we limited our analysis to urban extents with more than 50,000 residents in 2000; thus some of what appears to be peri-urban or rural emissions may in fact be emissions from small urban centers.

### 3.6 Covariates of urban GHG emissions

The regression results are consistent with expectations. Urban GHG emissions are most closely associated with population size (Table 4). Larger cities have more emissions, all else equal. The regression indicates a positive population scaling effect, where a small increase in population size in any particular area is associated with a disproportionately larger increase in emissions, on average. The scaling effect may well reflect the methods used by EDGAR to allocate emissions by population or population density for source categories such as

**Table 4** Determinants of variation in urban GHG emissions by development status

| Variable | All urban extents | Developed | Developing |
|---|---|---|---|
| Pop. | 1.414*** | 1.366*** | 1.424*** |
| | 0.014 | 0.025 | 0.017 |
| GDP/cap. | 0.418*** | 0.190*** | 1.058*** |
| | 0.033 | 0.041 | 0.089 |
| Pop. Den. | −0.646*** | −0.625*** | −0.609*** |
| | 0.027 | 0.054 | 0.031 |
| Pop. gr. rate | −8.095*** | −6.601*** | −7.581*** |
| | 1.269 | 2.259 | 1.509 |
| HDD + CDD | 0.009** | 0.006 | 0.007** |
| | 0.003 | 0.007 | 0.004 |
| Country ind. | 171 categories | 45 categories | 126 categories |
| N | 6327 | 1538 | 4789 |
| Adj-R2 | 0.845 | 0.828 | 0.797 |

Pop. = total population; GDP/cap = Gross domestic product per capita; Pop. Den. = population density of the entire urban extent; Pop. gr. Rate = population growth rate of the urban extents from 1990 to 2000; HDD + CDD = mean heating + cooling degree days; Country ind. = Country indicators. "All urban extents" include all the urban extents in our database

All variables transformed by natural log; robust standard errors on second line; *** $p<0.01$, ** $p<0.05$, *$p<0.1$

residences and off-road transport where detailed emissions location information were not available. Thus, the regression may attribute more of the variation in emissions across urban areas to population size than may be the case in reality.

The regression results indicate that cities with higher per capita incomes also have more emissions, although the income effect is considerably weaker than the population effect at explaining variation in urban GHG emissions. This finding also raises questions about the methods used by EDGAR to allocate emissions within a country. For instance, if high-income residents use more energy for residential heating and cooling than low-income residents and if high-income residents live disproportionately within a city, then the allocation of residential GHG emissions may be systematically underrepresented within urban areas when emissions are allocated only by population and not by a combination of population and income. The EDGAR documentation is clear that they do not account for income when allocating emissions by population. Thus, our analysis cannot distinguish the independent effect of income from population given the imprecision with which income is measured here for each urban area (as discussed above) and the likely but hidden interaction of population and income during construction of the EDGAR dataset.

The remaining regression results also fit with expectations. Denser cities have fewer emissions, all else equal, signaling a potential role for urban planning and policy in curtailing GHG emissions (i.e., transport, land use zoning, building codes, etc.). Faster growing cities also have substantially fewer emissions in 2000, all else equal. Evaluation of the standardized regression coefficients suggests that recent population growth is less well associated with total urban emissions than the contemporaneous size or affluence of the urban population. Last, the local climate appears to have only a weak and slightly positive effect on urban GHG emissions at the global scale, after controlling for other variables.

The results largely hold when grouping urban extents by region (Table 5). Larger cities have more emissions, all else equal, and population remains the strongest predictor of urban

**Table 5** Determinants of variation in urban GHG emissions by region

| Variable | Africa | Oceania | N. America | Asia | Europe | L. America & Carib |
|---|---|---|---|---|---|---|
| Pop. | 1.471*** | 1.570*** | 1.187*** | 1.431*** | 1.430*** | 1.473*** |
| | 0.056 | 0.334 | 0.051 | 0.018 | 0.029 | 0.051 |
| GDP/cap | 1.334*** | 0.398 | 0.156** | 1.328*** | 0.210*** | 0.518*** |
| | 0.274 | 0.261 | 0.069 | 0.146 | 0.053 | 0.102 |
| Pop. Den. | −0.656*** | −1.929** | −0.346** | −0.558*** | −0.653*** | −0.808*** |
| | 0.107 | 0.811 | 0.133 | 0.033 | 0.058 | 0.106 |
| Pop. gr. rate | −7.839 | 23.961 | −12.676*** | −6.799*** | −3.758 | −10.046*** |
| | 4.928 | 15.563 | 3.423 | 1.733 | 2.707 | 3.776 |
| HDD + CDD | 0.016 | −0.043 | −0.031 | 0.006 | 0.003 | 0.009 |
| | 0.012 | 0.110 | 0.038 | 0.004 | 0.007 | 0.112 |
| Country indicator (categories) | 47 | 7 | 2 | 48 | 40 | 27 |
| N | 649 | 39 | 324 | 3535 | 1136 | 644 |
| Adj-R2 | 0.805 | 0.795 | 0.833 | 0.786 | 0.798 | 0.776 |

Pop. = Total population; GDP/cap = Gross domestic product per capita; Pop. Den. = population density of the entire urban extent; Pop. gr. Rate = population growth rate of the urban extents from 1990 to 2000; HDD + CDD = mean heating + cooling degree days; Country ind. = Country indicators

All variables transformed by natural log; robust standard errors on second line; *** $p<0.01$, ** $p<0.05$, *$p<0.1$

emissions. Population density continues to have a substantively important negative association with emissions in all regions. Recent population growth continues to exhibit a strong negative association with emissions from cities in North America, Latin America, and Asia, but no statistically significant association with emissions from cities in Africa, Oceania, or Europe. Last, per capita income exhibits inconsistent associations with emissions across the different regions, with strong positive associations within Africa and Asia, modest positive associations in Europe, Latin America, and North America, and insignificant association in Oceania. The differences appear related to development status: the income effects appear smaller in high-income regions like North America and larger in regions with a wider range of per capita incomes like Asia. As with the global regression, however, we are uncertain about the extent to which the income and population findings can be distinguished given the methods used to construct the EDGAR inventory and the covariate datasets.

### 3.7 Comparison of individual urban area GHG emissions and regional and global GHG emission estimates with bottom-up studies

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 compared (Hoornweg et al. 2011b). We are reluctant to compare our results for any particular area to these "bottom-up" estimates, given known and sizable differences in methodology regarding urban geographic boundaries, included gases and source sectors, conversion factors, and the years studied. Nevertheless, we do so here to illustrate a point about usability of our top-down methodology.

Table SI.6 demonstrates that of the 32 urban areas evaluated by both "bottom-up" studies and with corresponding locations in our dataset, only 3 area estimates fall within our ranges. Our "top-down" estimates differed from between −64.5 and 115.6 % of the "bottom-up" estimates found in the literature. Figure SI.5 plots these differences in percentage terms. Note that a negative number signals that our high estimate is lower than that in the literature and a positive number that our low estimate is higher than that in the literature.

The absolute differences between our estimates and those in the literature for "bottom-up" studies vary between −7.3 tons $CO_2$-eq. per capita and 7.6 tons $CO_2$-eq. per capita (Figure SI.6). When the estimates are aggregated at the regional and global scales, however, the differences decrease. For example, the mean difference of average $CO_2$-eq. tons per capita and our top down estimates in Asia are −2.25, while those for Europe are −0.5 (Figure SI.7). At the global scale, the mean difference between estimates is −0.46 $CO_2$-eq. tons per capita, suggesting that at this scale our estimates are only slightly lower than the mean for the individual bottom up urban studies that we examined.

The conversion of estimates at higher scales, plus valued feedback from our peers, suggests that our "top-down" methodology is most appropriate for regional and global scale analyses. Further standardization of a protocol such as the recently announced ICLEI/C40/WRI GHG emissions accounting procedure will go a long way towards improving the accuracy of GHG emissions estimates for comparison across individual urban areas (ICLEI, C40 and World Resources Institute 2012).

## 4 Discussion

This exploratory analysis uses a combination of existing datasets and independent top-down analysis to find that urban areas contribute less than half of global GHG emissions of $CO_2$,

$CH_4$, $N_2O$, and $SF_6$. Our results fall closer to some previous estimates (see, Satterthwaite 2008) than others (IEA 2008). In general, we expect differences between estimates due to important methodological distinctions. First, as discussed here and in the supplement, our underlying emissions dataset (EDGAR) may introduce uncertainties into the estimation of emissions for urban areas that would not be present in studies using different emissions datasets. For instance, EDGAR 4.0 data use population and population density as proxies for allocating some GHG emissions spatially where more detailed information is not available (i.e., residential and waste), inherently implicating these variables as explanatory. EDGAR 4.0 does not use affluence (GDP) as a proxy, which could systematically underestimate emission in high-density areas where urbanites have higher incomes and use more energy than their rural counterparts.

Second, this study examines a larger complement of gases and emissions sources than have been studied to date at the global scale. Indeed, our high estimate of energy-related GHG emissions (66.3 %) is only slightly lower than a previous study's estimate of energy-related $CO_2$ emissions (71 %) (IEA 2008). Our estimate provides a wider view of sources contributing to urban GHG emissions.

Third, we examine a wide variety of cities of different sizes and across the world. Both size and development status of cities appear to be important influences on their GHG emissions. Most of the "bottom-up" studies have been performed on cities in the developed world and typically on large cities. It is possible that previous estimates of urban emissions worldwide may be overstated, as they typically derive their estimates from cities in the developed world (for an exception to this trend and this result see Dhakal 2009).

At the individual city level we find that there are differences between our estimates and those reported in the literature. When aggregated at higher scales, the differences between these estimates decrease, thus independently confirming previous studies and suggesting that our "top-down" methods are best used for regional and global scale analysis. Given the resolution of the EDGAR 4.0 data, we do not expect our urban level estimates to match those of studies performed at smaller scales.

This study confirms that a small number of larger cities appear responsible for the lion's share of urban GHG emissions worldwide (Hoornweg et al. 2011b). At the same time, it also suggests that some of the highest per capita emitters make up a small percentage of total urban GHG emissions. Together these findings can help to focus policy priorities.

The differences in per capita emissions levels between urban and non-urban areas suggest that in the developing world urban emissions levels can be higher than those in non-urban areas, not least due to better energy and transport infrastructure. Indeed, urban emissions levels in parts of Asia are higher than that found in the developed world (Dhakal 2009). This pattern may be less apparent in South America because the region is highly urbanized (i.e., that more than 75 % of the population is already living in dense settlements) (United Nations 2010).

This study points to the potential importance of peri-urban areas as sites of emissions in the developing world, something that may have been overlooked in previous urban GHG studies. To our knowledge there have not been any significant studies of this important area in developing countries. Our results suggest further examination of peri-urban GHG emissions is warranted.

The regression results point to similarities and differences between regions for covariates of GHG emissions. The population scaling effect noted in this study for GHG emissions and urban population (i.e., that larger cities may be less efficient than smaller ones) has been of recent interest to urban analysts (Fragkias et al. 2013) and more work is needed in this area.

Finally, these results are important to the research community because 1) the datasets incorporated are publicly available and this analysis points to their limitations and usefulness; 2) the analysis independently confirms previous findings regarding energy-related emissions; and 3) the results suggest some areas for further work.

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## References

Bader N, Bleischwitz R (2009) Measuring urban greenhouse gas emissions: the challenge of comparability. Surv Perspect Integrat Environ Soc 2:7–21

Balk D, Pozzi F, Yetman G, Deichmann U, Nelson A (2004) The distribution of people and dimension of place: methodologies to improve the global estimation of urban extents. CIESEN, Columbia University, New York

Bangkok Metropolitan Administration (2007) Action plan on global warming mitigation 2007–2012. BMA, Bangkok

Bloomberg MR (2007) Inventory of New York City Greenhouse Gas Emissions. New York City Mayor's Office of Operations, Office of Long-term Planning and Sustainability

Brown MA, Southworth F, Sarzynski A (2008) Shrinking the carbon footprint of metropolitan America. Brookings Institute Metropolitan Policy Program, Washington DC

Butler TM, Lawrence MG (2009) The influence of megacities on global atmospheric chemistry: a modelling study. Environ Chem 6:219–225

Butler TM, Lawrence MG, Gurjar BR, van Aardeene J, Schultz M, Lelieveld J (2008) The representation of emissions from megacities in global emission inventories. Atmos Environ 42:703–719

Croci E, Melandri S, Molteni T (2011) Comparing mitigation policies in five large cities: London, New York City, Milan, Mexico City and Bangkok. In: Hoornweg D, Freire M, Lee MJ, Bhada-Tata P, Yuen B (eds) Cities and climate change: responding to an urgent agenda. World Bank, Washington, D.C, pp 55–85

Dhakal S (2009) Urban energy use and carbon emissions from cities in China and policy implications. Energy Policy 37:4208–4219

Dhakal S (2010) GHG emission from urbanization and opportunities for urban carbon mitigation. Curr Opin Environ Sustain 2:277–283

Dietz T, Rosa EA (1997) Effects of population and affluence on CO2 emissions. Proc Natl Acad Sci 94:175–179

Elvidge CD, Baugh KE, Kihn EA, Kroehl HW, Davis ER (1997) Mapping city lights with nighttime data from the DMSP operational linescan system. Photogramm Eng Remote Sens 63:727–734

Fragkias M, Lobo J, Strumsky D, Seto KC (2013) Does size matter? Scaling of CO2 emission and US urban areas. PLoS ONE 8:e64727. doi:10.1371/journal.pone.0064727

Grubler A, Bai X, Buettner T, Dhakal S, Fisk DJ, Ichinose T, Keirstead JE, Sammer G, Satterthwaite D, Schulz NB, Shah N, Steinberger J, Weisz H (2012) Chapter 18: urban energy systems. In: Global Energy Assessment (ed) Global energy assessment - toward a sustainable future. Cambridge University Press, Cambridge, pp 1307–1400

Hillman T, Ramaswami A (2010) Greenhouse gas emission footprints and energy use benchmarks for eight U.S. Cities. Environ Sci Technol 44:1902–1910

Hoffert MI, Caldeira K, Jain AK, Haites EF, Harvey LDD, Potter SD, Schlesinger ME, Schneider SH, Watts RG, Wigley TML, Wuebbles DJ (1998) Energy implications of future stabilization of atmospheric $CO_2$ content. Nature 395:881–884

Hoornweg D, Freire M, Lee MJ, Bhada-Tata P, Yuen B (2011a) Cities and climate change: responding to an urgent agenda. World Bank, Washington, D.C., pp 15–54

Hoornweg D, Sugar L, Lorena C, Gomez T (2011b) Cities and greenhouse gas emissions: moving forward. Environ Urban 23:207–227

ICLEI, C40 & World Resources Institute (2012) Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC), Pilot Version 1.0. ICLEI, C40, WRI

IEA (2008) World energy outlook 2008. OECD/IEA, Paris
IPCC (2007) Climate change 2007: synthesis report. IPCC, Geneva
Kennedy C, Ramaswami A, Carney S, Dhakal S (2011) Greenhouse gas emission baselines for global cities and metropolitan regions. In: Hoornweg D, Freire M, Lee MJ, Bhada-Tata P, Yuen B (eds) Cities and climate change: responding to an urgent agenda. World Bank, Washington, D.C., pp 15–54
Kenworthy JR, Laube F, Newman PWG, Barter PA, Raad T, Poboon C, Guia B (2000) An international sourcebook of automobile dependence in cities, 1960–1990. University Press of Colorado, Colorado
Marcotullio PJ, Albrecht J, Sarzynski A (2011) The geography of greenhouse gas emissions from within urban areas of India: a preliminary assessment. Resour, Energy Dev 8:11–35
Marcotullio PJ, Sarzynski A, Albrecht J, Schulz N (2012) The geography of urban greenhouse gas emissions in Asia: a regional analysis. Glob Environ Chang 22:944–958
New M, Lister D, Hulme M, Makin I (2002) A high-resolution data set of surface climate over global land areas. Clim Res 21:1–25
Olivier JGJ, Bouwman AF, Van Der Mass CWM, Berdowski JJM (1994) Emissions Database for Global Atmospheric Research (EDGAR). Environ Monit Assess 31:93–106
Olivier JGJ, Bouwman AF, Van der Hoek KW, Berdowski JJM (1998) Global air emission inventories for anthropogenic sources of NOx, NH3 and N2O in 1990. Environ Pollut 102:135–148
Ramaswami A, Hillman T, Janson B, Reiner M, Thomas G (2008) A demand-centered methodology for city-scale greenhouse gas inventories. Environ Sci Technol 42:6455–6461
Rosenzweig C, Solecki WD, Hammer S, Mehrotra S (2011) Climate change and cities, first assessment report of the urban climate change research network. Cambridge University Press, Cambridge
Sarzynski A (2012) Bigger is not always better: a comparative analysis of cities and their air pollution impact. Urban Stud 49:3115–3132. doi:10.1177/0042098011432557
Satterthwaite D (2008) Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. Environ Urban 20:539–549
Schulz N (2010) Delving into the carbon footprint of Singapore - comparing direct and indirect greenhouse gas emissions of a small and open economic system. Energy Policy 38:4848–4855
Sovacool BK, Brown MA (2010) Twelve metropolitan carbon footprints: a preliminary comparative global assessment. Energy Policy 38:4856–4869
UNDP (2002) World development report: deepening democracy in a fragmented world. Oxford University Press, New York
UN-Habitat (2011) Global report on human settlements 2011, cities and climate change. Earthscan, London
United Nations (2010) World urbanization prospects: 2009 revisions. DESA, UN, New York
Waggoner PE, Ausubel JH (2002) A framework for sustainability science: a renovated IPAT identity. Proc Natl Acad Sci 99:7860–7865
WBCSD and WRI (2004) A corporate accounting and reporting standard. World Business Council for Sustainable Development and World Resources Institute, Conches-Geneva
York R, Rosa EA, Dietz T (2003) STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. Ecol Econ 46:351–365