Global anthropogenic emissions in urban areas: patterns, trends, and challenges

Monica Crippa, Diego Guizzardi, Enrico Pisoni, Efisio Solazzo, Antoine Guion, Marilena Muntean, Aneta Florczyk, Marcello Schiavina, Michele Melchiorri, Andres Fuentes Hutfilter

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

Global anthropogenic emissions in urban areas: patterns, trends, and challenges

To cite this article: Monica Crippa *et al* 2021 *Environ. Res. Lett.* **16** 074033

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
4 February 2021

REVISED
19 April 2021

ACCEPTED FOR PUBLICATION
13 May 2021

PUBLISHED
6 July 2021

LETTER

Global anthropogenic emissions in urban areas: patterns, trends, and challenges

Monica Crippa[1,*], Diego Guizzardi[1], Enrico Pisoni[1], Efisio Solazzo[1], Antoine Guion[1,4], Marilena Muntean[1], Aneta Florczyk[1], Marcello Schiavina[1], Michele Melchiorri[2] and Andres Fuentes Hutfilter[3]

[1] European Commission, Joint Research Centre (JRC), Ispra, Italy
[2] Engineering S.p.a, Piazzale dell'Agricoltura 24, 00144 Roma, Italy
[3] OECD, 2, rue André Pascal Cedex 16, Paris 75775, France
[4] Present address: LMD/IPSL, Sorbonne Université, ENS, PSL Université, École polytechnique, Institut Polytechnique de Paris, CNRS, Paris, France.
[*] Author to whom any correspondence should be addressed.

E-mail: monica.crippa@ec.europa.eu

Keywords: urban emissions, climate change mitigation, urban air quality, sustainable development, global emissions, Emissions Database for Global Atmospheric Research (EDGAR)

Supplementary material for this article is available online

Abstract

Between 1970 and 2015 urban population almost doubled worldwide with the fastest growth taking place in developing regions. To aid the understanding of how urbanisation has influenced anthropogenic CO_2 and air pollutant emissions across all world regions, we make use of the latest developments of the Emissions Database for Global Atmospheric Research. In this study, we systematically analyse over 5 decades of emissions from different types of human settlements (from urban centres to rural areas) for different sectors in all countries. Our analysis shows that by 2015, urban centres were the source of a third of global anthropogenic greenhouse gases and most of the air pollutant emissions. The high levels of both population and emissions in urban centres therefore call for focused urban mitigation efforts. Moreover, despite the overall increase in urban emissions, megacities with more than 10 million inhabitants in high-income countries have been reducing their emissions, while emissions in developing regions are still growing. We further discuss per capita emissions to compare different types of urban centres at the global level.

1. Introduction

Between 1970 and 2015 the global population increased by 80%, of which the global urban population almost doubled, while the global rural population increased by only 40% [1]. The urban population increased in all continents [2, 3]. The fastest urban population growth occurred in developing and emerging regions, notably Africa (by 3.1 times), Latin America (by 2 times), Oceania (by 1.7 times) and countries like India (by 2.7 times) and China (by 1.8 times). Lower urban population growth rates are found in North America (by 1.5 times), Europe (by 1.3 times), Japan (by 1.2 times) and Russia (by 1.1 times) [4]. By 2015, almost half of the global population lived in urban centres, while the largest urban centres with more than 1 million inhabitants were only 5% of the total, but had 22% of the world's population [4] living in them.

As the '2030 Sustainable Development Agenda' reports, a key goal is to achieve sustainable cities balancing economic growth, social inclusion and environmental protection to satisfy current needs without compromising the ability of future generations to satisfy their needs [5]. Reaching this goal is challenging since urban centres are typically characterised by densely concentrated economic activities generating high environmental pressures. The eleventh Sustainable Development Goal (SDG11) 'Sustainable cities and communities' states that 'cities and metropolitan areas are powerhouses of economic growth—contributing about 60% of global GDP. However, they also account for about 70% of global carbon emissions and over 60% of resource use. The rapid urbanisation is often associated to a worsening air pollution' [6]. SDG13 'Climate Action' also deals with climate change related issues where urban areas play a significant role: 'Governments and businesses should utilize the lessons learned to accelerate the transitions needed to achieve the Paris Agreement, redefine the relationship with the environment and make systemic shifts and transformational changes to lower greenhouse gas emissions and climate-resilient economies and societies' [7, 8].

From a sustainability perspective, the capacity to identify the nature, location and source of emissions is important, in particular where localised air pollutant hotspots expose population to high air pollution concentration levels. Local emissions data are also important to design locally tailored policy approaches to climate change mitigation. A place-based approach is important so that climate policy can take into account local wellbeing co-benefits, including climate change mitigation and air pollution [9], as well as socio-economic vulnerabilities, which depend on local economic activities, infrastructure and social conditions. A place-based approach is also important for the support of local citizens, businesses and governments. Local and regional governments have substantial responsibility for many decisions to reduce emissions and air pollution, for example, in transport and land use. Therefore, it is important to map where emissions happen, to be able to tailor emission reduction policies to their geographical sources and sectors.

Gathering information on emissions from densely populated areas at the global level is complex due to the lack of consistency and harmonisation between emission inventories at local level [10, 11]. Inventories can differ in methodology [12 –14], sectoral detail and availability of emission time series, which are needed to understand trends and the effectiveness of policy implementation.

This study is a first attempt to provide from a country-level to a global view the evolution of sector-specific air pollutant and greenhouse gas (GHG) emissions from urban centres (and other geographical entities) for different types of human settlements over the past 5 decades. The Emissions Database for Global Atmospheric Research (EDGAR) underpins this analysis. The EDGAR database is a global emission inventory that estimates emissions mainly using international statistics as activity data (e.g. fuel balance statistics from IEA [15], FAO data [16], USGS data, etc.) and emission factors from the IPCC guidelines [17] and EMEP/EEA Guidebook [18]. In addition, knowledge from scientific literature is included to provide more accurate emission estimates for specific sectors and countries, as reported by Janssens-Maenhout *et al* [19].

The consolidated version 5 of EDGAR [20–22] represents the state of the art within the emission inventory communities characterising current and historic emissions of air pollutants and GHGs at the global, regional and country level. EDGAR provides spatio-temporal homogeneous consistent GHG and air pollutant emissions at the global scale from 1970 to 2015 [19, 23]. EDGAR spatially distributes anthropogenic emissions over a global gridmap with a spatial resolution of 0.1° (about 10 km), enabling the investigation of where emissions happen and supporting the development of place-based mitigation measures from global to local level. Owing to its global coverage and consistency, recent applications of EDGAR include policy consultation [21, 24, 25] and design of mitigation actions, including contributions to the Fifth and Sixth Assessment reports of the Intergovernmental Panel on Climate Change (IPCC). With the aim of increasing its outreach and exploitation, one of the latest EDGAR developments is the implementation of high spatial resolution proxies serving the purpose of mapping different types of settlement layers. This approach, combined with the latest population statistics (see supplementary material (available online at stacks.iop.org/ERL/16/074033/mmedia)), allows a detailed characterisation of emissions in cities, functional urban areas (FUAs), dense and semi-dense clusters, suburban and peri-urban, and rural areas [26, 27]. This latest development aims to promote EDGAR as a reference inventory also for mapping emissions released in urban areas. More in detail, new population-based proxies have been developed using settlement types obtained from the GHS–SMOD settlement classification grid at Level 2 [28, 29] defined as 'very low density rural areas', 'low density rural areas', 'rural clusters', 'suburban or peri-urban areas', 'semi-dense urban clusters', 'dense urban clusters', and 'urban centres' (see also table S1)[26].

Compared to previous studies [30, 31], the novelties of this work are the detailed spatial distributions of emissions of both GHG gases (CO_2 and non-CO_2) and air pollutants from urban settlements, calculated for different activities; all of which are available for the past 45 years.

2. Methods

2.1. The global human settlement layer (GHSL)

The GHSL produces global data and information about the human presence on Earth. It is produced with artificial intelligence techniques by combining Earth observations satellite data, demographic data and other open geospatial data (i.e. reference data or thematic data). The GHSL maps built-up areas, population and settlement typologies at multiple spatial and temporal resolutions that are freely available online[5] following three core principles for data production: (a) test and apply real-world (big) data scenarios, (b) produce evidence-based output analytics, and (c) facilitate repeatability of the results [32].

Satellite records, like the Landsat data collection that is the primary input for the production of the

[5] https://ghsl.jrc.ec.europa.eu/datasets.php.

multi-temporal built-up area layers (GHS–BUILT), are the foundation of GHSL data production. The Built-up layer maps the 'union of all the satellite data samples that corresponds to a roofed construction above ground which is intended or used for the shelter of humans, animals, things, the production of economic goods or the delivery of services' [33]. GHS–BUILT is obtained by large scale processing of satellite data records with symbolic machine learning method [34]. Freire *et al* [35] used the GHS–BUILT as covariate for a dasymetric disaggregation of demographic data from CIESIN GPWv4.10 to produce a global multi-temporal population grid (GHS–POP, [36]). The combination of the GHS–BUILT with GHS–POP and ancillary data were used by Florczyk *et al* [29] to develop a global layer that identifies seven settlement typologies (see table S1) with 1 km spatial resolution (GHS–SMOD, [28]). This Settlement Model (GHSL–SMOD[29]) uses population density thresholds and connected components population size thresholds to classify the urban—rural continuum. Urban Centres, Dense Urban Clusters and Semi-dense Urban Clusters, Suburban or peri-urban grid cells form the urban domain. Low-density rural grid cells and Very low-density rural grid cells and Rural clusters form the rural domain (see table S1). The GHS–SMOD applies to the globe the stage 1 methodology for delineation of cities and urban and rural areas called 'Degree of Urbanisation'. This methodology has been adopted by the United Nations Statistical Commission [37, 38] for international and regional statistical comparison purposes.

Based on the GHS–SMOD, the spatial entities corresponding to the Urban Centre class were used to collect multi-dimensional and multi-temporal attributes by means of spatial integration [39]. The resulting information system is the Urban Centre Database (GHS–UCDB), an analysis ready dataset on urban centres [2]. The GHS-UCDB is suitable for a backward analysis of the temporal changes that occurred within today's urban centre (as of 2015).

This article is based on analytics derived from GHS–UCDB spatial entities and its multi-temporal attributes, population and emissions.

2.2. The Emissions Database for Global Atmospheric Research (EDGAR)

EDGAR provides consistent GHG and air pollutant emissions at the global scale from 1970 to 2015 [19, 23] and spatially distributed anthropogenic emissions over a global gridmap at 0.1° spatial resolution for all anthropogenic emitting sectors with the exception of Land Use, Land Use Change and Forestry. The year 2015 represents in EDGAR the latest year for which air pollutant emissions are available. This was constrained by the lack of more recent statistical data (activity data, emission factors, technologies and abatement measures) needed for the emissions computation when this study was conducted. New population-based proxies have been developed in the EDGARv5.0 database using the seven settlement types delineated in the GHS–SMOD settlement classification grid at Level 2 [28] with 1 km spatial resolution for four epochs (1975, 1990, 2000 and 2015). Distribution of emission data (that are a continuous series) over the proxies (that are based on GHSL epochs 1975, 1990, 2000, 2015) follows the logic of the closer available year (e.g. emissions of 1980 are distributed over the proxy of 1975, emissions of 2010 are distributed over the 2015 proxy, etc.). This methodology is already applied within the EDGAR database in cases of lack of continuous spatial data to cover the entire time series. In this study this choice is motivated by the need of changing both the population intensity trend and its spatial allocation to the different type of settlements over the continuous time series, which is the driving component; however the corresponding data are not available. Given its high spatial resolution and temporal coverage, the GHS–SMOD was considered the most suitable data source for the update of the population proxy in EDGAR. The development of a new set of population proxy data (derived in-house) led to some considerable improvements for emission distribution on gridmaps in EDGAR. The finer resolution of the data source (from 2.5 arc-minutes of CIESIN GPWv3 to 30 arc-seconds in the 4th version) and the use of satellite imagery brought an increase of accuracy and precision. The main improvements are:

- the use of population data source with a higher number of subnational geographical units (around 30 times more) from CIESIN GPWv4.
- moving from one reference year to four reference years when calibrating the population classes.
- an updated methodology of the settlement classification by using spatial criteria on population and built up density and therefore allowing to define a degree of urbanisation into seven classes for each cell of the grid.

Using more accurate population gridmaps should increase the quality of the emissions distribution in EDGAR, emissions gridmaps that are largely used in atmospheric modelling and policymaking.

In order to produce the EDGARv5.0 population-based proxies (table S2) from the GHSL products [28], some spatial processing has been performed in Python 3.6 and ArcMap 10.4, as depicted in figure S1. The previous EDGAR population based proxies, used in all EDGAR releases up to EDGAR v4.3.2, only distinguished between rural and urban population density maps as basis to distribute population-related emissions and as gap filling proxy (see table S3).

The main improvement of EDGARv5.0 population-based proxies consists in defining detailed proxies for small scale combustion activities with sub-sector and fuel dependent classification, as reported in table S4. In particular, emissions from combustion in the agricultural sector are distributed over 'low and very low density rural areas' for all fuels with the exception of natural gas which is assumed to be used as fuel mainly in 'rural cluster'. Emissions from combustion in the household/commercial/other sectors are attributed over 'total population' density maps for all fossil fuels, with the exception of natural gas which is allocated to the 'connected' proxy. The combustion of biofuels in the household/commercial/other sectors is allocated to the 'non-urban' proxy, assuming therefore a lower use of biofuels compared to other fuels in urban centres.

Table S5 provides an overview of all the proxies used in the current EDGARv5.0 version in comparison with the previous release (EDGARv4.3.2, [19]). In general, the gap-filling proxies using urban population have been substituted with the 'connected' proxy, in order not to concentrate all emissions from industries and processes, which could not be allocated to point sources, to urban areas. As a result, these industrial emissions are distributed over a wider area and do not impact only urban centres, determining lower emissions over urban areas in EDGARv5.0 compared to EDGARv4.3.2.

Figures S2 and S3 show the difference in the v5.0 CO_2 2015 emission allocation (https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG) using the EDGARv5.0 and EDGARv4.3.2 proxies, both in absolute and relative terms. Major differences are found over urban areas in particular over Europe and North America, where the new EDGARv5.0 proxies allocate less emissions compared to the former version. This result mainly reflects the assumptions behind each EDGAR proxy dataset, in fact EDGARv4.3.2 used urban population as gapfilling proxy, thus allocating to urban areas also all industrial (and other sources) emissions when no point source information was available (see also table S5). Moreover, lower emissions over urban areas are due to the allocation of emissions from biofuel combustion (e.g. combustion of solid biomass in the residential sector) largely to rural areas and not anymore to the total population density distribution.

2.3. Sectorial aggregation of the emissions

EDGAR provides emissions of GHGs and air pollutants for all anthropogenic emitting sectors, following the IPCC categories, with the exception of Land Use, Land Use Change and Forestry. In this work results are presented for aggregated sectors, namely 'energy-industry' (which includes the combustion in the power and non-power generation industries, fugitive emissions, fuel production, refineries and transformation industries), 'residential' (which includes small scale combustion), 'transport' (which includes both road and non-road transport), 'waste' (which includes solid waste disposal and waste water treatment) and 'other' (which includes all emissions not included in the other categories such as industrial process emissions (e.g. cement production, iron and steel production, non-metallic minerals production, non-ferrous metals productions, chemicals production), solvent use, indirect emissions for N2O, etc.).

3. Results

3.1. Emissions are concentrated in urban centres requiring focused mitigation actions

In 2015 urban centres represented only 0.5% of the global land and sea surface [4], (Esch *et al* [40]), but produced approximately one third of anthropogenic emissions of CO_2 (35%) and the following proportions of NO_x (29%), PM10 (27%), CO (26%), SO2 (37%) emitted world-wide (figure 1). Expanding the definition of urban areas to include suburbs, roughly 50% of global emissions cover around 1% of the global surface. Finally, when including all urban areas and not only urban centres, around 70%–80% of global emissions are included, consistently with the findings of Ribeiro *et al* [41]. These emissions are mostly driven by combustion sources. The only exception is NH3, where rural areas account for more than 50% of global emissions, mainly associated with agricultural activities. In 1970, the proportion of total emissions from urban centres were lower and on average 20% for NO_x, PM10 and CO, 26% for CO_2, 27% for SO2 and 5% for NH3. The proportion of global emissions from wider urban areas were also lower ranging from 40% to 70% depending on the pollutant (figure 1). As recently pointed out by e.g. Ribeiro *et al* (2019), these figures make urban centres key to the implementation of mitigation strategies and solutions to the global climate change problem. As reported in tables S1–S3 these shares are heterogeneous and depend on the income level of the country and on the pollutant (see also figure 2).

Looking at the different regional patterns of the proportion of total CO_2 emitted in urban centres, these are higher in Asian countries characterised by high population densities (e.g. Japan, 55% of the country total) and in emerging economies like China and India (44%), but also in Middle East (51%) and North Africa (46%). By contrast, urban centres in Europe (20%–29%) and North America (22%) are characterised by a lower proportion of total emissions, in part due to the more frequent siting of high CO_2-emitting activities, such as power plants, outside urban centres [12] and also due to different urban structures. Low shares of CO_2 emissions from urban centres are also associated with less developed regions

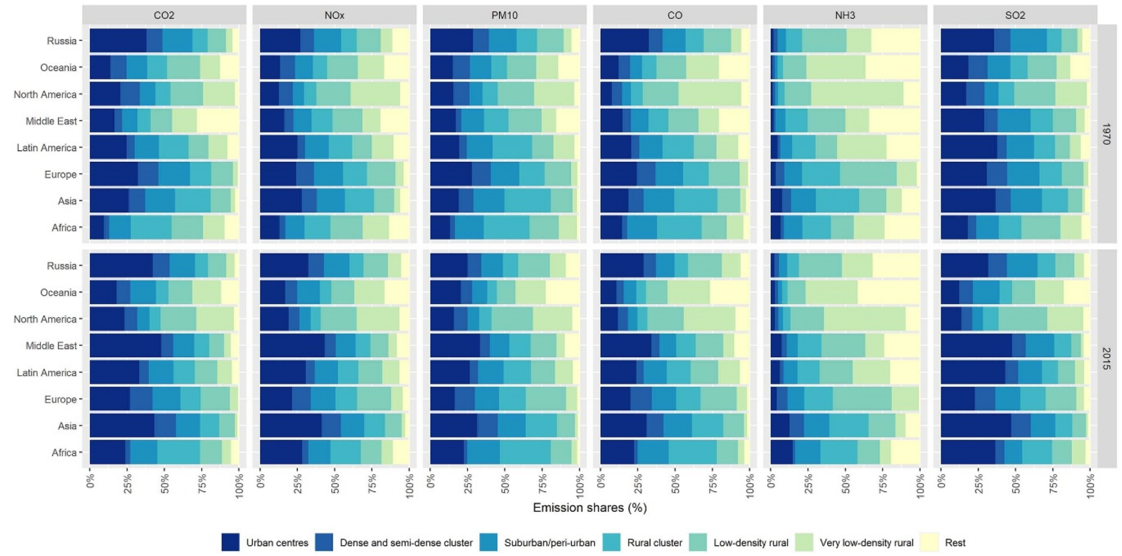

Figure 1. Comparison of emission shares by settlement type in 1970 and 2015 for key world regions. The category 'Rest' represents the difference between total emissions and those allocated in the different settlement areas (i.e. emissions occurring overseas, coastal areas, flaring, etc.).

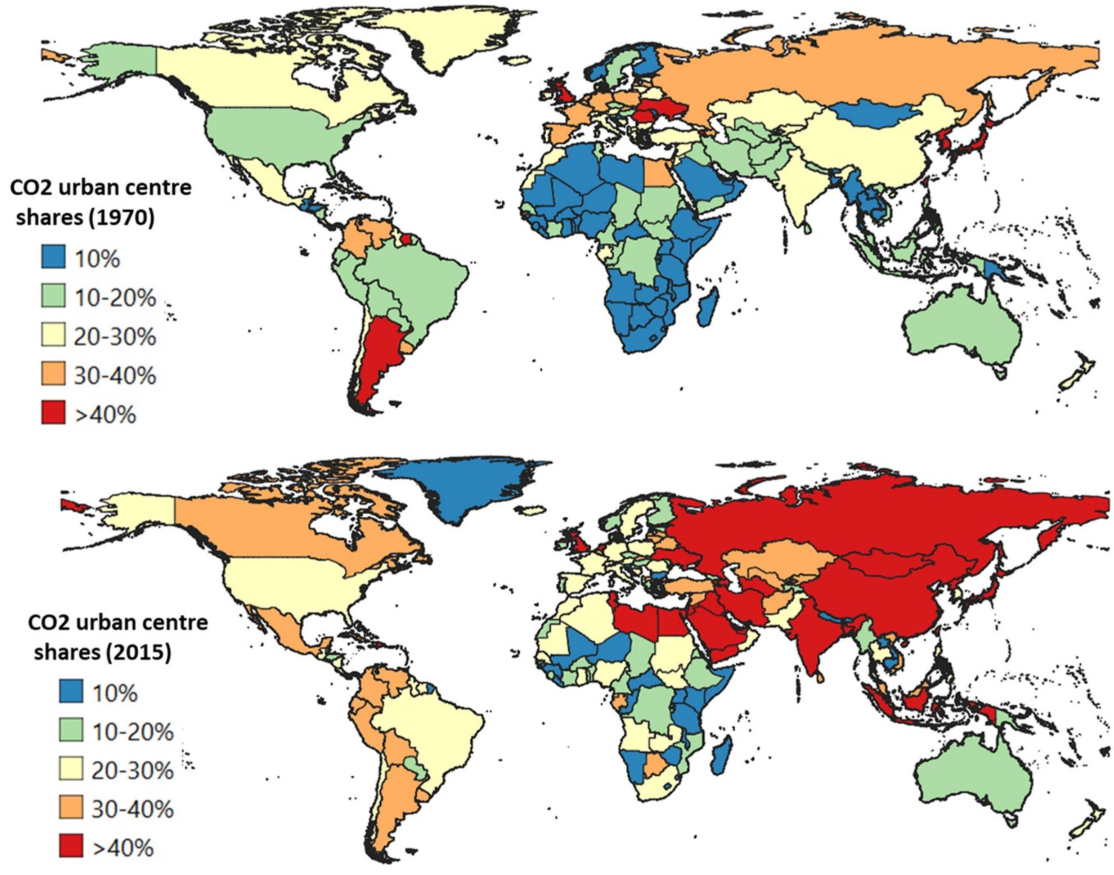

Figure 2. Share of CO_2 emissions from urban centres in 1970 and 2015 by country.

such as some central and southern African countries and Oceania (less than 20%).

In China, per capita CO_2 emissions from urban centres increased by approximately 520% from 1970 to 2015 while national per capita CO_2 emissions over the period has increased by 293%. By contrast in the USA the same figures decreased by 45% and 17% respectively. This result illustrates how urbanisation in middle-income and fast-growing countries is frequently associated with sharply rising emissions (and yet urbanisation is continuing). Similar regional patterns are found for NO_x and PM_{10}, where low shares of emissions from urban centres in industrialised countries can in part be attributed to policy measures and technological advancements in reducing air pollutant emissions from anthropogenic activities and to the de-localisation of high CO_2 emitting industrial facilities. Since GHGs and air pollutants are often co-emitted by the same sources, this reflects the possible co-benefits between air quality and climate change policies in reducing them. This result highlights the need to develop measures targeting urban emissions at the global scale in order to abate almost a third of global air pollutant emissions. However, when looking for example at the combustion of biomass as fuel, although being carbon neutral, it is highly polluting in terms of air quality and the implementation of very strict and specific regulations is required[42]. This example represents a trade-off between climate change and air quality policies and it is therefore crucial, when designing mitigation options, considering both air quality and climate goals.

3.2. Combustion related sources mostly contribute to the emissions in urban centres

Emissions of air pollutants and CO_2 in urban centres are mostly associated with combustion activities related to the production of energy as well as its use in industrial processes, and the residential and transport sectors. For example, at global level NO_x is mostly emitted by the energy-industry (69%) and transport sectors (24%), with a higher share from transport in industrialised regions (29%), and in countries mostly using gasoline vehicles (e.g. North America). CO emissions come mainly from the transport sector, with a global share of 36%, which increases up to 47% in urban centres of industrialised regions. However, CO, SO_2 and PM_{10} emissions decreased from 1970 to 2015 in industrialised regions despite the increase in fuel consumption, thanks to the higher energy efficiency and implementation of new technologies and abatement measures. By contrast, NH_3 is mostly emitted in rural areas, rural clusters and dense or semi-dense urban clusters, although 9% of NH_3 emissions still happens in urban centres. NH_3 is emitted not only from agriculture, but also from transport and waste. NH_3 emissions are increasing in particular in urban centres, while NO_x emissions are rather stable. In less developed regions contributions come also from the power-industry sector and residential. Figure S4 shows the sectorial composition of the emissions from FAUs (FUAs, [43]) in 1970 and 2015 for different pollutants and world regions.

3.3. Emissions in urban centres increased strongly in emerging economies in the past 5 decades but decreased in high-income economies

Emissions varied across settlement types over the years, for example, CO_2, NO_x and PM_{10} emissions showed the fastest growth in urban centres compared to the other settlement classes from 1970 to 2015 both for developing and industrialised countries, reflecting the enhancement of anthropogenic activities related with combustion processes (figure 3). On the contrary, over the same time period CO emissions showed reductions in urban centres due to more efficient combustion in particular in industries and their relocation outside urban centres, while they increased in urban clusters and rural areas in particular in developing countries. A different pattern is found for NH_3 with the fastest growth happening in urban centres in industrialised countries (in particular in North America and to a lesser extent in the EU) due to the deployment of selective catalytic reduction systems to abate NO_x (which produce NH_3 as a by-product) [44], while NO_x emissions are rather stable. Finally, SO_2 emissions decreased over the past decade, mainly in urban centres thanks to the implementation of fuel quality directives and international treaties, which lead to the desulphurisation of the fuel used in vehicles, power plants and industries, while they increased in the other settlement classes in developing regions [45]. Globally, emissions in urban centres increased from 1970 to 2015 for all pollutants, in particular due to higher emissions from developing countries. CO, SO_2 and PM_{10} emissions in industrialised countries decreased thanks to the higher energy efficiency and implementation of new technologies and abatement measures (figure 3).

Our analysis also identifies the relevance of CH4 emissions in urban centres as summarised in table 1, showing the rate of change in CH_4 emissions in urban centres in the period 1970–2015. Urbanisation has indeed a deep impact on CH_4 emissions, favouring a six-fold faster increase in total emissions from urban centres with respect to the aggregated emissions (30% vs. 5% for industrialised regions and 358% vs. 59% for developing regions). The only exception is Europe, where the urban CH_4 emissions decrease faster than the total CH_4 emissions, driven by a steep reduction in the residential sector. The emission sectors driving the sharp CH_4 rise in urban centres are energy, transport (mainly in Asia) and waste (Africa and Latin America).

3.4. Megacities in industrialised countries have been reducing their emissions while in developing regions they are still growing

The number of megacities (with population higher than 10 million inhabitants) and very large urban

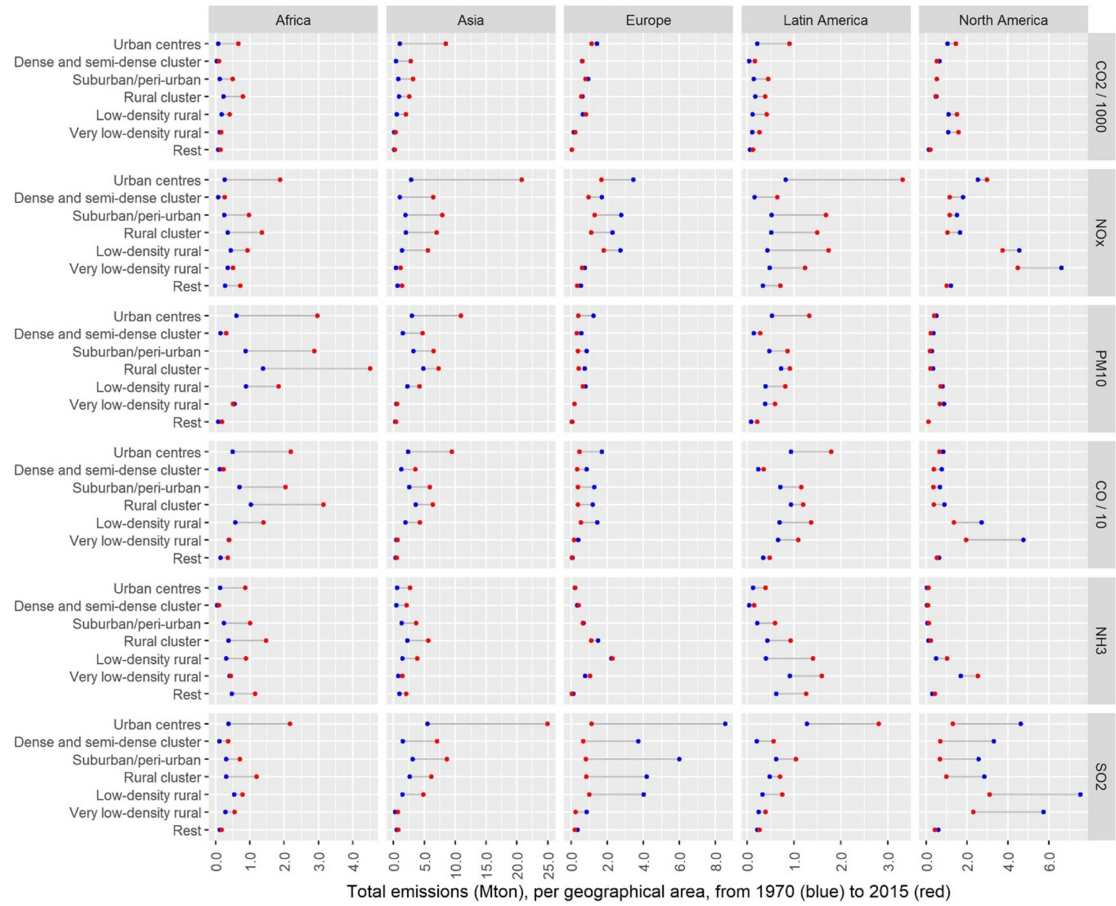

Figure 3. Emission changes from 1970 (blue dots) to 2015 (red dots) for each pollutant, continent and settlement type. The category 'Rest' represents the difference between total emissions and those allocated in the different settlement areas (i.e. emissions occurring overseas, coastal areas, flaring, etc.). Country aggregation into continents is shown in the map of figure S6.

Table 1. CH_4 emission change in the period 1970–2015 for aggregated regions in terms of total emissions and of emission from urban centres. The last column indicates the sectors where the largest changes have occurred.

	CH_4 total emissions (2015 vs. 1970) (%)	CH_4 emissions in urban centres (2015 vs. 1970) (%)	Predominant sectors driving the change in urban centres (2015 vs. 1970)
Industrialised	5	30	Waste (+55%)
Developing	59	358	Transport (+1242%); Energy (+733%)
Africa	83	643	Waste (+1003%)
Asia	61	257	Transport (+1618%)
Europa	−29	−39	Residential (−79%)
Latin America	79	371	Energy (+323%); Waste (+409%)
North America	0	36	Agriculture (+429%); Energy (+268%)
Oceania	64	89	Agriculture (+298%); Energy (+474%)
Russia	48	115	Energy (+205%); Waste (+135%)

centres strongly increased from 1970 to 2015 [4], in particular over Asia. In 1970, 11 global megacities (Tokyo, Kyoto, Mexico City, Kolkata, Seoul, New York, Jakarta, Guangzhou, Mumbai, São Paulo and New Delhi) accounted for 2.2% and 1.8% of global CO_2 and $PM_{2.5}$ emissions, respectively. When also including very large urban centres (26 agglomerations), these high emitting areas are still mainly located in Asian region, including also several European and American urban centres (Los Angeles, Paris, London, Moscow and Chicago) and accounted for 4.7% and 2.6% of global CO_2 and $PM_{2.5}$ emissions

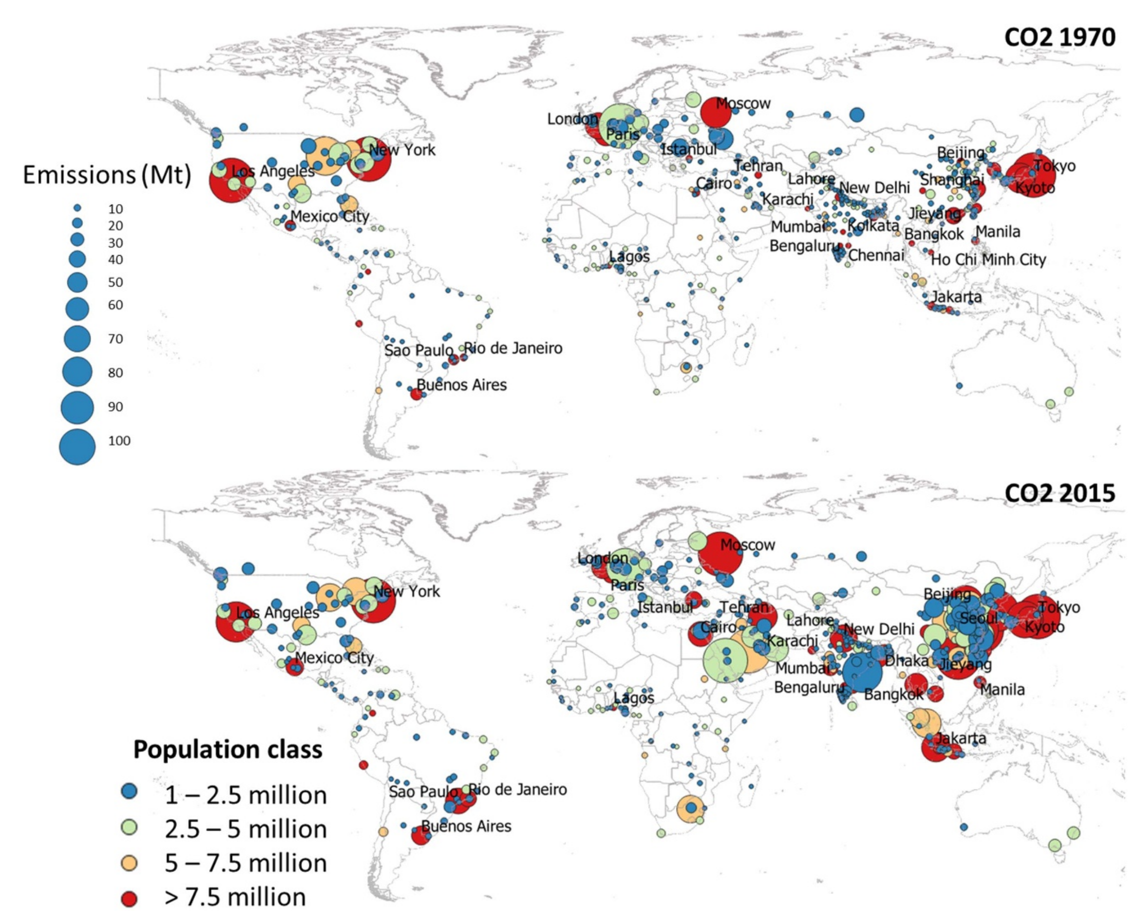

Figure 4. Evolution of CO_2 emissions in urban centres from 1970 to 2015. The size of the bubbles is proportional to CO_2 emissions. Megacities with a population of more than 10 million people in 2015 are represented with their names (population class considered: 2015).

respectively. Due to the fast urbanisation and the emerge of megacities at the global level, in 2015 the number of megacities almost tripled compared to 1970 (for a total of 32) and represented 12% and 4.6% of total CO_2 and $PM_{2.5}$ emissions. These shares strongly increase when considering also the very large urban centres (71 at global level), reaching 17.7% and 6.7% for CO_2 and $PM_{2.5}$, respectively. Moran *et al* [30] find that roughly 18% of global CO_2 emissions is emitted by 100 cities, which is consistent with our finding of 20.2% of CO2 emissions from top emitting urban centres in 2015. Figure 4 shows that CO_2 emissions are high for all megacities and tend to increase over time, in particular in emerging economies. By contrast, $PM_{2.5}$ emissions decreased by approximately 40% in industrialised countries over the past 4 decades (figure 6). These results are also confirmed by the analysis shown in figures 5 and 7, where emissions from countries belonging to different income classes are clustered. For total CO_2 (figure 5) the bending of the pattern with respect to the 1:1 line shows that large cities from less developed economies are those where CO_2 emissions have grown the most since 1970, whereas large cities from North America, Europe and Japan—although having high CO_2 emissions—have stalled their emissions over time. On average (i.e. the average of the variation rate between 1970 and 2015) we observe for $PM_{2.5}$ emitted in large urban centres (>5 M inhabitants) (a) a decrease of approximately 40% in more developed regions (MDR) and (b) an increase of 280% and in excess of 600% in less developed countries (LDC) and least developed countries (LDCL), respectively. The same analysis applied to CO_2 reveals (a) a weak increase (6%) of CO_2 emissions in MDR (thus the 'stalling'), (b) an increase of 780% of CO_2 emissions in LDC, and (c) an increase of 970% of CO_2 emissions in LDCL.

Total $PM_{2.5}$ emissions for very large urban centres (figure 7(b) confirm the faster rise of urban emissions in developing economies with respect to megacities in developed economies whose 2015s emissions are lower (e.g. Paris, London, Nagoya), or approximately at the same level (e.g. Dallas, Los Angeles, Toronto) of those of 1970 (figures 6 and 7).

3.5. High-income countries have decoupled their emissions from economic growth

In the past 25 years (1990–2015), the urbanisation process (increase of urban population) and economic growth in Europe and North America was decoupled from CO_2 and $PM_{2.5}$ emissions, which

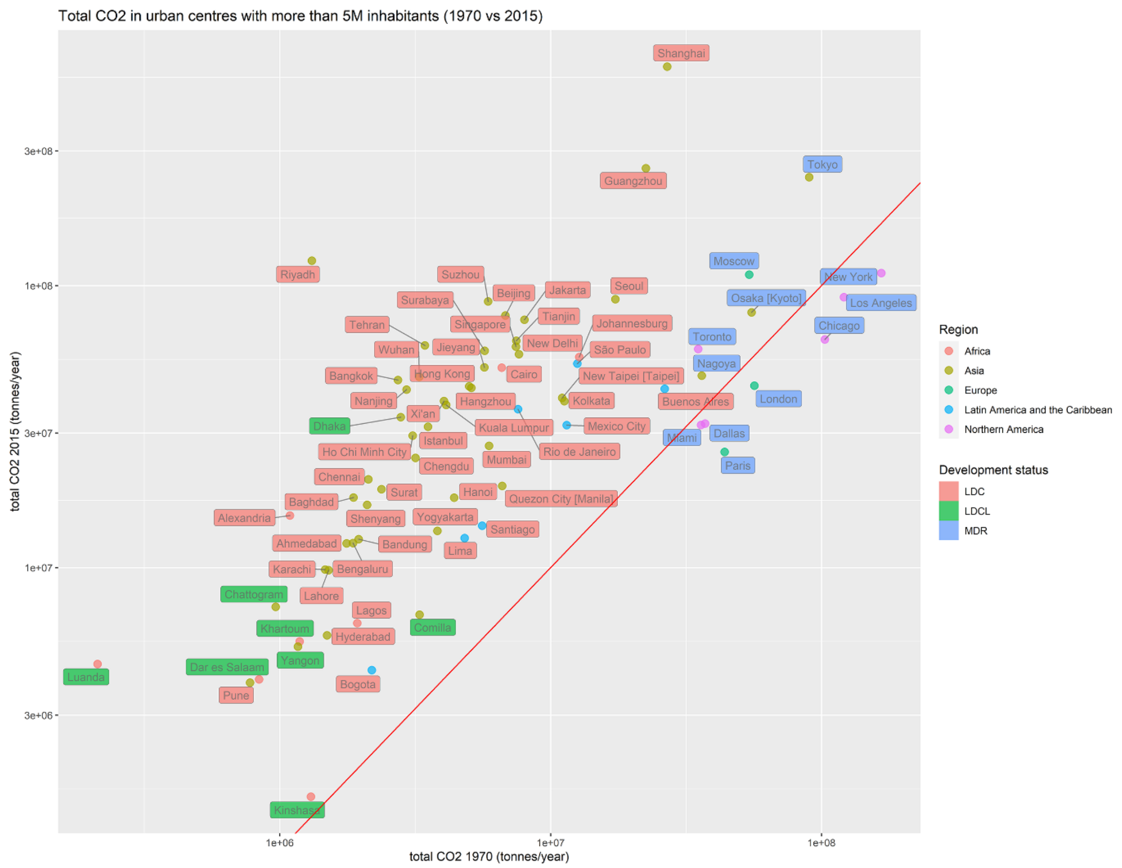

Figure 5. Comparison of total CO_2 emissions (tons, logarithm scale) in 1970 and 2015 in very large urban centres with a population higher than 5 million, classified by income class (LDC: less developed countries; LDCL: least developed countries; MDR: more developed regions [46]) and region is also represented.

have been reduced despite the increase of population in urban areas and economic growth. This result has been achieved thanks to the introduction of mitigation measures at national but also local scale, which effectively reduced air pollutant emissions, enhanced energy efficiency, deployed less carbon intense fuels and relocation of power plants and industrial facilities. A very different picture is found on average for Asian urban centres, where the emissions of air pollutants and CO_2 were not decoupled from the economic and population growth since 2000. Asian megacities belonging to high income countries show the slowest growth in the emissions and some similar features compared to those of high-income countries, while urban centres of low and middle income countries show on average an increase of their emissions over the past 15 years by around two times (up to 18 times higher in the case of Berhampore–Beldanga in India, eight times higher for Putian in China, and seven times higher for Kabul in Afghanistan) [47]. Increasing emissions together with population and GDP are found for highly populated urban areas in Latin America and Africa, mostly belonging to upper-medium income and low-income countries, respectively.

Although real GDP of the EU, USA and China has gone upwards, the USA and Europe, as mature wealthy economies, have decoupled economic growth from urban emissions and the total population grows at the same pace as the urban population, while urban emissions decrease much faster than the total one [48, 49]. The evolution of population, CO_2 (figure S5(a)), and $PM_{2.5}$ (figure S5(b)) illustrates the differential speed of urban centre emissions with respect to the regional total, most notably for PM2.5 in Asia, driven by the fast urbanisation of China, where the fastest changes are found from 2000 onwards. The comparison with mature economies (EU27+ UK and USA) reveals a consolidated and decreasing trend of $P_{2.5}$ and CO_2 emissions faster in urban centres than at national level, that is decoupled from GDP (increasing steadily in both regions) and from urban population (albeit stable in EU27+UK and slowly rising in the USA). China on the other hand has been fastly developing, its urban population has been growing faster than the total population and urban emissions are still in the fast ascending phase, quicker than the country total [50, 51]. In a recent study, Ruixe *et al* [52] use satellite data on air pollution, for the period from 2001 to 2018 together with data on fossil fuel carbon dioxide emissions from a global inventory. The joint analysis of these data with GDP has shown that air pollution is mostly linked to the pace of economic growth while for CO_2 the connection

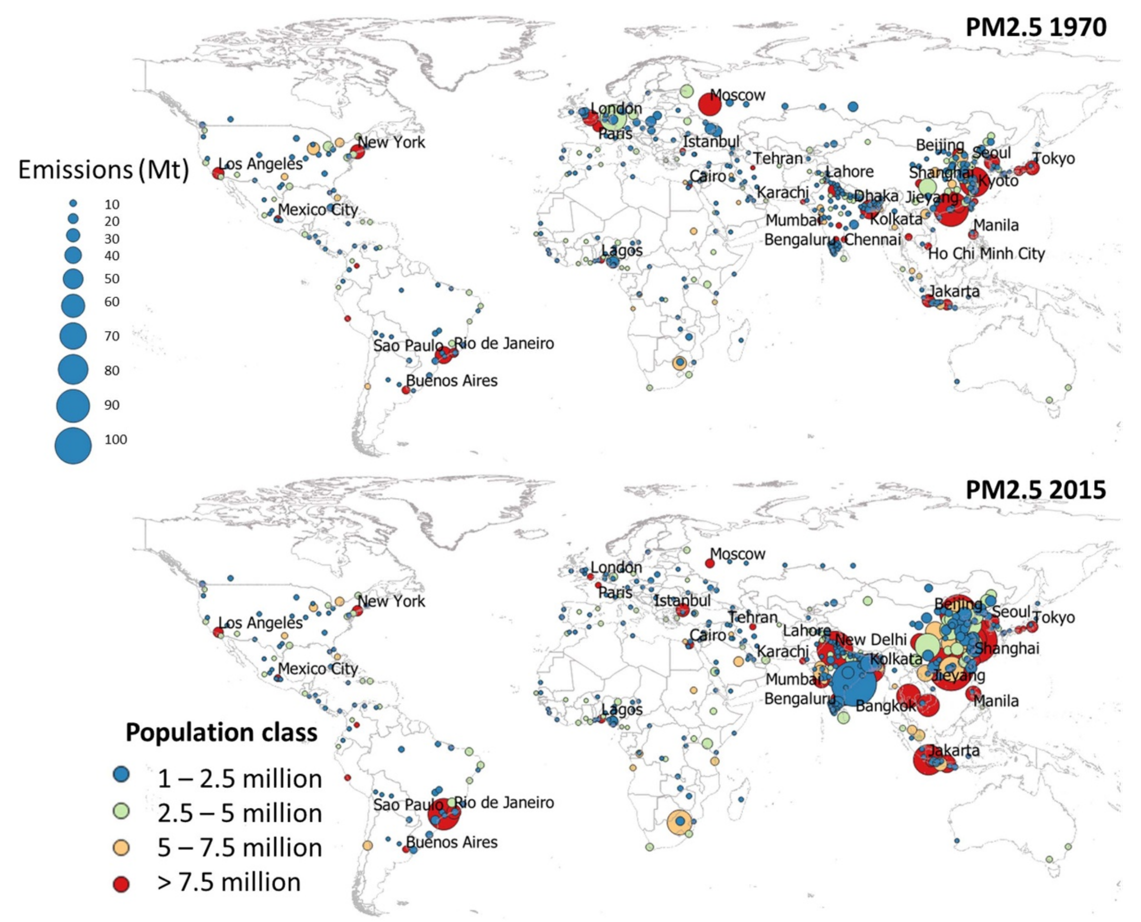

Figure 6. Evolution of $PM_{2.5}$ emissions in urban centres from 1970 to 2015. The size of the bubbles is proportional to $PM_{2.5}$ emissions. Megacities with a population of around 10 million people in 2015 are represented with their names (population class considered: 2015).

is even more straightforward: countries with high GDP also have high fossil fuel emissions. Nonetheless, as the cases of Europe and North America show, a decoupling between economic growth and emissions is achievable.

3.6. Per capita CO_2 emissions show spatial differences, at global level

Per capita CO_2 emissions from urban centres by continent (figure 8) show that Asia is by far the continent with the largest number of urban settlements and together with Africa has the largest variation of CO_2 per capita emissions, independently of the population size. On average, in China large urban centres are more CO_2 demanding (per inhabitant) than small ones. North America, by contrast, has a very high and homogeneous urban CO_2 consumption across its territory and small urban areas, on average, consume approximately as much as large ones.

There were 72 large urban centres in China in 2015 (43 in 1970) and 31 (19) in the USA. The number of very large urban centres were 3 (3) in 1970 in China (USA) and became 13 (5) in 2015. In the time span 1970–2015, the urban centre areas of China experienced a demographic growth of 76% and built-up areas expansion of 161% [4]. CO_2 emitted in these Chinese urban centre areas has grown by 1000% (541% per capita). Energy production (+1800%) and transport (+1300%) are the sectors where the rise is more pronounced. The biggest increase is registered in very large urban centres, while the lowest growth is observed in urban centres with a population between 0.25 M and 0.5 M inhabitants. The maximum increase per capita (∼900%) is however observed for areas with 75000–0.1 M inhabitants rather than in megacities where, by contrast, the minimum increase per capita is detected (244%). In absolute terms, looking at the 2015, the per capita emissions of urban centres with 1 M to 2 M inhabitants are the less sustainable (12.6 ton CO_2 per capita^{-1} year^{-1}), above the per capita emissions (9 ton CO_2 per capita^{-1} year^{-1}) of very large cities (>5 M inhabitants).

Over the same 45 years time span (1970–2015), the trend is the opposite for USA and Europe[6]. USA urban centres areas have registered an increase of 52% in both built up surfaces and urban population with a decrease in the same area of 17% of CO_2

[6] Europe is here defined as EU27 + UK.

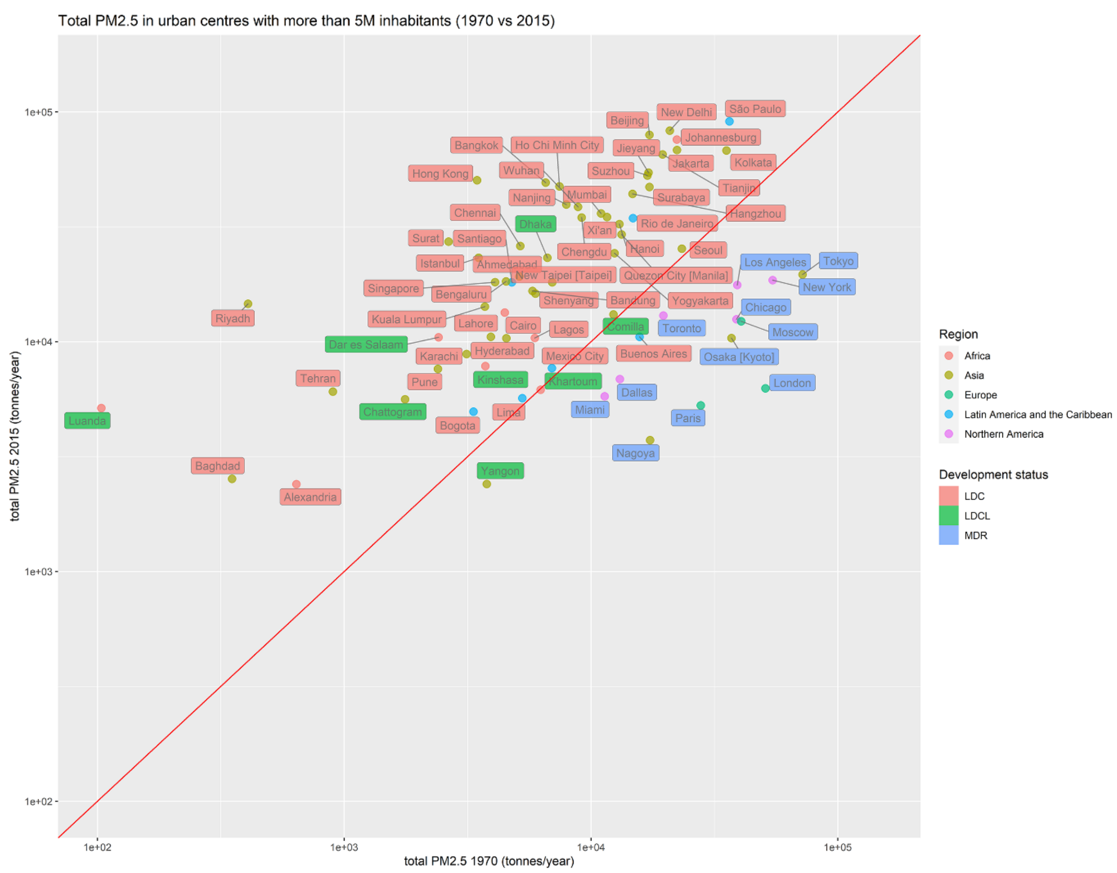

Figure 7. Comparison of total $PM_{2.5}$ emissions (tons, logarithm scale) in 1970 and 2015 in very large urban centres with a population higher than 5 million, classified by income class (LDC: less developed countries; LDCL: least developed countries; MDR: more developed regions [46]) and region is also represented.

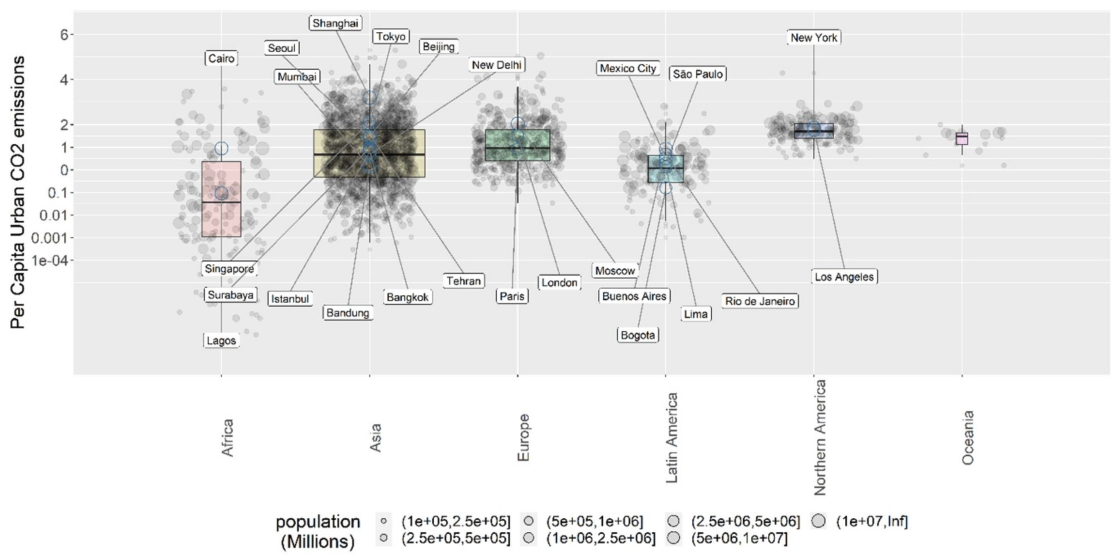

Figure 8. Per capita urban CO_2 emissions by continent (expressed in tonnes CO_2/person). The size of the box corresponds to the number of urban centres, the dots represent the distribution and their size is proportional to the population. Some representative cities are indicated for reference.

(−45% per capita) emissions driven by residential (−30%) and industrial (−36%) sectors, while energy (+30%) and transport (+60%) have continued to rise. European urban centre areas experienced demographic growth of 14% and built-up areas expansion of 24% and CO_2 emissions in the same area have declined by 33%, driven by drastic drop in transport (−85%) energy (−44%) and industry (−50%) sectors. Per capita CO_2 emissions of urban population in Europe have decreased by 33% in 40 years. While in the USA the largest decrease (−49%) in CO_2 emissions is observed for urban centres with population between 0.5 and 1 M, and the minimum (−4%) for urban centres between 0.075 M and 0.1 M inhabitants, in Europe all urban sizes show a consistent decrease from −36% (0.075 M to 0.1 M inhabitants) to −54% (0.5 M to 1 M inhabitants). The CO_2 per capita emissions are levelled to ~6 ton CO_2 per capita^{-1} for all urban sizes in the US, much less than in China, but more than in Europe, where they range between 2.60 ton CO_2 per capita (50 000–75 000 inhabitants) and 5.5 ton CO_2 per capita (2 M to 5 M inhabitants).

4. Discussion

In EDGAR, emissions are first computed at national level with very detailed sectorial disaggregation, including information for roughly 60 type of fuels, hundreds of technologies and abatement measures over the time period 1970–2015. As a second step, national emissions by sub-sector and fuel are spatially distributed over the globe making use of around 300 spatial proxies taking into account country specific information, fuel characteristics, population and type of urban settlements etc. (refer to the description of the spatial proxies provided above and in Janssens-Maenhout *et al* [19]). The resulting emission gridmap has a resolution of 0.1° (roughly 10 km) although several of the original spatial proxies were computed using information at higher resolution (e.g. point sources, road network, GHSL data at 1 km spatial resolution, etc.).

In order to retrieve information on specific urban centres, a shape file ('SMOD_v9s10_HDC_list_2015_HG0_HDC_ll.shp', https://ghsl.jrc.ec.europa.eu/datasets.php) has been overlapped to the EDGAR gridmaps and the corresponding emissions have been extracted for each sector, pollutant, etc.

The main advantage of our approach consists in providing a global picture of urban centre emissions and of other type of settlements over almost 5 decades for all air pollutants and GHGs. It is often the case that literature studies focus mainly on CO_2 emissions or on very recent years [30], preventing the analysis of how emissions evolved over time for different type of settlements, the investigation of urbanization process together with the quantification of the corresponding emissions and the analysis of air pollutants which are detrimental for human health in particular in densely populated areas such as megacities. In addition, EDGAR provides a consistent view at global level, since the same methodology is applied both for national emissions calculation and spatially distributed data, allowing the comparability of the results amongst countries. Getting a complete, consistent and comparable picture of emissions by settlement type at the global level for all air pollutants and GHGs is challenging since no global compilation of urban centre emissions exists.

On the other hand, our approach has some limitations related with the spatial resolution (i.e. a 0.1° × 0.1° resolution is low when needing to investigate specific urban features such as canyons, congestion, emissions from individual buildings, etc.), with the assumptions behind the spatial proxies used and lack of detailed or up to date spatial information for certain regions/sectors. To overtake this shortcoming, we apply a gapfilling procedure, using a backup proxy mostly based on population related spatial data when specific spatial data are not available or not enough accurate (e.g. missing point sources, industrial facilities, waste plants, etc.).

A complete validation of the EDGAR emissions is very complex and cannot be done in a systematic way at the global level. The EDGAR data are validated against measurements of air pollutants through the use of chemical transport models [53] or through inverse modelling in particular for GHGs [19, 54]. In 2018, the Global Carbon Budget used the spatial patterns of the EDGAR grid maps and might give feedback on the spatial representativeness in the future. Another source of uncertainty in emission inventories comes from the spatial dimensions; in literature, up to 100% spatial uncertainty can be found for specific areas, especially at the urban-rural transitioning areas [55].

5. Conclusions

In this work we have used a consistent methodology to identify the most polluting areas all over the world. This can serve to define adequate mitigation measures to reduce CO_2 and air pollutants emissions, in cities. This study pertains with the quantification and trends of pollutant and GHG emissions in inhabited areas, globally. It provides a snapshot of the potential of having a database of historic urbanization coupled with economic indicators, emissions by sector and population. As an example, we zoomed into specific sectors and individual countries (China, USA and Europe), showing the impact of the degree of urbanisation on emissions and we show the potential of the database and of the analysis to support sector-specific mitigation strategies. We have shown that urban centres have different potential in reducing air pollutant and CO_2 emissions compared to the national level. Therefore, specific measures should be developed for cities to reduce air pollution and climate change to better contribute to the achievement of national emission reduction targets. In particular, policies could be focussed on key emitting sectors and most polluted areas/hot spots, to significantly improve global air quality and guarantee a sustainable future.

Our analysis, which looks at the time period 1970–2015, different sectors, pollutants and various geographical aggregations shows that:

- urban centres make a large contribution to global air pollutant and CO_2 emissions, and being these emissions spatially concentrated (on about 0.5% of global surface), they can benefit from geographically focused mitigation actions;
- combustion related sources mostly contribute to the emissions from urban centres;
- emissions in urban centres fell in high-income economies and increased strongly in emerging economies over the past 5 decades;
- for megacities, emissions in high-income countries have been reduced thanks to the implementation of effective mitigation actions, de-industrialisation and the growth of the service economy which allowed to decouple their emissions from economic growth;
- per-capita urban CO_2 emissions show spatial differences at global level, among different countries and cities.

While climate change is a global issue, air quality is a more local problem to be tackled in order to reduce urban population exposure to harmful pollutants and finally to reduce human health impacts and those on ecosystems. Local actions are therefore needed for both climate and air pollution. From this point of view, city level actions can be effective to reduce $PM_{2.5}$ population exposure; as shown in Thunis *et al* [56] for European cities, a 30% $PM_{2.5}$ reduction can be achieved with urban actions in at least half of the considered cities. However, for air pollution exposure (and in particular for $PM_{2.5}$ exposure) it is important to complement local actions with NH_3 mitigation measures focussed on rural areas to reduce the secondary component of $PM_{2.5}$.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://data.europa.eu/doi/10.2904/JRC_DATASET_EDGAR. The GHSL data collection is available at https://data.jrc.ec.europa.eu/collection/ghsl and more specifically the GHS-UCDB can be found at http://data.europa.eu/89h/53473144-b88c-44bc-b4a3-4583ed1f547e and the GHS-SMOD at http://doi.org/10.2905/42E8BE89-54FF-464E-BE7B-BF9E64DA5218.

Acknowledgments

The authors are grateful to Julian Wilson for the review of the manuscript. The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission. The designations employed and the presentation of materials and maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory or area or of its authorities, or concerning the delimitation of its frontiers or boundaries that if shown on the maps are only indicative. The boundaries and names shown on maps do not imply official endorsement or acceptance by the European Union.

Author contributions

MC, DG, AG and MM designed and developed the new spatial proxies in the EDGAR database; ES and EP analysed the data and drafted relevant parts of the manuscript; AF, MS and MM developed the GHSL datasets and contributed to the manuscript; AFH helped with the identification of key messages and results interpretation; MC designed and supervised the project and drafted most of the paper.

ORCID iDs

Monica Crippa https://orcid.org/0000-0002-7143-7117
Efisio Solazzo https://orcid.org/0000-0002-6333-1101
Aneta Florczyk https://orcid.org/0000-0001-8912-1500
Marcello Schiavina https://orcid.org/0000-0003-3399-3400
Michele Melchiorri https://orcid.org/0000-0002-3009-8868

References

[1] Melchiorri M F, Freire A J, Schiavina S, Kemper M, Kemper M and Unveiling T 2018 25 years of planetary urbanization with remote sensing: perspectives from the global human settlement layer *Remote Sens.* **10** 768
[2] Florczyk A J *et al* 2019 GHS Urban Centre Database 2015, multitemporal and multidimensional attributes, R2019A *European Commission, Joint Research Centre (JRC) [Dataset]* (available at: http://data.europa.eu/89h/53473144-b88c-44bc-b4a3-4583ed1f547e)
[3] Dijkstra L P 2014 A harmonised definition of cities and rural areas: the new degree of urbanization *Directorate-General for Regional and Urban Policy* Working Papers
[4] European Commission 2018 Atlas of the human planet 2018—a world of cities *EUR 29497 EN* (Luxembourg: Joint Research Centre, European Commission) p JRC114316
[5] United Nations 2017 General assembly resolution 71/256, New Urban Agenda *A/RES/71/256* (available at: undocs.org/en/A/RES/71/256) (Accessed 25 January 2017)
[6] United Nations 2019 The sustainable development goals report (New York: United Nations)
[7] Rosenzweig C, Solecki W, Hammer S A and Mehrotra S 2010 Cities lead the way in climate—change action *Nature* **467** 909–11
[8] Satterthwaite D 2008 Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions *Environ. Urban.* **20** 539–49
[9] Shaddick G, Thomas M L, Mudu P, Ruggeri G and Gumy S 2020 Half the world's population are exposed to increasing air pollution *Npj Clim. Atmos. Sci.* **3**
[10] Nangini C *et al* 2019 A global dataset of CO_2 emissions and ancillary data related to emissions for 343 cities *Sci. Data* **6**

[11] Pulles T 2017 Did the UNFCCC review process improve the national GHG inventory submissions? *Carbon Manage.* **8** 19–31
[12] Kennedy C *et al* 2010 Methodology for inventorying greenhouse gas emissions from global cities *Energy Policy* **38** 4828–37
[13] Ellis J A S M 2015 Identifying and addressing gaps in the UNFCCC reporting framework *OECD/IEA Climate Change Expert Group Papers, No. 2015/07* (Paris: OECD Publishing) (https://doi.org/10.1787/5jm56w6f918n-en)
[14] United Nations Framework Convention on Climate Change 2017 2017 guide for peer review of National GHG Inventories (available at: www.un-gsp.org/sites/default/files/documentos/guide_for_peer_review_of_national_ghg_inventories_002.pdf)
[15] IEA 2017 Energy balance statistics for 1970-2015 (available at: www.iea.org/)
[16] FAO 2018 (available at: www.fao.org/faostat/en/#home)
[17] IPPC 2006 Guidelines for National Greenhouse Gas Inventory *Volume 5: Waste* (available at: www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html)
[18] EMEP/EEA 2019 EMEP/EEA air pollutant emission inventory guidebook 2019 *European Environment Agency* (Luxembourg: Publications Office of the European Union) (https://doi.org/10.2800/293657)
[19] Janssens-Maenhout G *et al* 2019 EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012 *Earth Syst. Sci. Data* **11** 959–1002
[20] Crippa M , Guizzardi D, Muntean M, Schaaf E, Oreggioni G and Solazzo E EDGARv5.0 2019 (available at: https://edgar.jrc.ec.europa. eu/overview.php?v=50_GHG)
[21] Crippa M *et al* 2019 Fossil CO_2 and GHG emissions of all world countries—2019 report *EUR 29849 EN* (Luxembourg: Publications Office of the European Union) p JRC117610
[22] Oreggioni G D *et al* 2020 Climate change in a changing world: socio-economic and technological transitions, regulatory frameworks and latest trends on global greenhouse gas emissions from EDGAR v5.0 *Glob. Environ. Change* accepted
[23] Crippa M *et al* 2018 Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4.3.2 *Earth Syst. Sci. Data* **10** 1987–2013
[24] Muntean M, Guizzardi D, Schaaf E, Crippa M, Solazzo E, Olivier J G J and Vignati E 2018 Fossil CO_2 emissions of all world countries—2018 report *EUR 29433 EN* (Luxembourg: Publications Office of the European Union) p JRC113738
[25] Crippa M *et al* 2020 Fossil CO_2 emissions of all world countries—2020 report *EUR 30358 EN* (Luxembourg: Publications Office of the European Union) p JRC121460
[26] European Commission and Statistical Office of the European Union 2021 Applying the degree of urbanisation—a methodological manual to define cities, towns and rural areas for international comparisons—2021 edition *Publications Office of the European Union* (https://doi.org/10.2785/706535)
[27] European Commission 2020 Atlas of the Human Planet 2020—open geoinformation for research, policy and action *2020 EUR 30516 EN, Publications Office of the European Union, Luxembourg, 2021* (Luxembourg: European Commission)
[28] Pesaresi M, Florczyk A, Schiavina M, Melchiorri M and Maffenini L 2019 GHS-SMOD R2019A—GHS settlement layers, updated and refined REGIO model 2014 in application to GHS-BUILT R2018A and GHS-POP R2019A, multitemporal (1975-1990-2000-2015) *European Commission, Joint Research Centre (JRC)* (https://doi.org/10.2905/42E8BE89-54FF-464E-BE7B-BF9E64DA5218)
[29] Florczyk A J *et al* 2019 GHSL data package 2019 *EUR 29788 EN* (Luxembourg: Publications Office of the European Union) p JRC117104
[30] Moran D *et al* 2018 Carbon footprints of 13 000 cities *Environ. Res. Lett.* **13** 064041
[31] Moran D, Kanemoto K, Jiborn M, Wood R, Többen J and Seto K C 2018 Carbon footprints of 13,000 cities *Environ. Res. Lett.* **13** 064041
[32] Melchiorri M P, Florczyk M, Corbane A J and Kemper C 2019 Principles and applications of the global human settlement layer as baseline for the land use efficiency indicator—SDG 11.3.1 *ISPRS Int. J. Geo-Inf.* **8** 96
[33] Pesaresi M *et al* 2013 A global human settlement layer from optical HR/VHR RS data: concept and first results *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **6** 2102–31
[34] Corbane C *et al* 2019 Automated global delineation of human settlements from 40 years of Landsat satellite data archives *Big Earth Data* **3** 140–69
[35] Freire S *et al* 2020 Enhanced data and methods for improving open and free global population grids: putting 'leaving no one behind' into practice *Int. J. Digital Earth* **13** 61–77
[36] Schiavina M, Freire S and MacManus K 2019 GHS population grid multitemporal (1975, 1990, 2000, 2015) R2019A *European Commission, Joint Research Centre (JRC)* (https://doi.org/10.2905/42E8BE89-54FF-464E-BE7B-BF9E64DA5218)
[37] United Nations 2020 Report on the fifty-first session *Statistical Commission* (available at: https://unstats.un.org/unsd/statcom/51st-session/documents/2020-37-FinalReport-E.pdf)
[38] United Nations 2020 A recommendation on the method to delineate cities, urban and rural areas for international statistical comparisons (available at: https://unstats.un.org/unsd/statcom/51st-session/documents/BG-Item3j-Recommendation-E.pdf)
[39] Florczyk A J *et al* 2019 Description of the GHS Urban Centre Database 2015 *Public Release 2019, Version 1.0* (Luxembourg: Publications Office of the European Union) p JRC115586
[40] Esch T *et al* 2017 Breaking new ground in mapping human settlements from space—The Global Urban Footprint *ISPRS J. Photogramm. Remote Sens.* **134** 30–42
[41] Ribeiro H V, Rybski D and Kropp J P 2019 Effects of changing population or density on urban carbon dioxide emissions *Nat. Commun.* **10** 3204
[42] Muntean M *et al* 2021 The health and climate benefits of a fuel and technology shift in small combustion: the biomass dilemma *Nat. Commun.* accepted
[43] Dijkstra L and Veneri P H 2019 The EU-OECD definition of a functional urban area *OECD Regional Development Working Papers, No. 2019/11* (Paris: OECD Publishing) (https://doi.org/10.1787/d58cb34d-en)
[44] Crippa M, Janssens-Maenhout G, Guizzardi D and Galmarini S 2016 EU effect: exporting emission standards for vehicles through the global market economy *J. Environ. Manage.* **183** 959–71
[45] Crippa M *et al* 2016 Forty years of improvements in European air quality: regional policy-industry interactions with global impacts *Atmos. Chem. Phys.* **16** 3825–41
[46] United Nations 2019 World urbanization prospects: the 2018 revision (ST/ESA/SER.A/420). *Department of Economic and Social Affairs, Population Division* (New York: United Nations)
[47] Wu Y, Zhu Q and Zhu B 2018 Decoupling analysis of world economic growth and CO_2 emissions: a study comparing developed and developing countries *J. Cleaner Prod.* **190** 94–103
[48] Sanyé-Mengual E, Secchi M, Corrado S, Beylot A and Sala S 2019 Assessing the decoupling of economic growth from environmental impacts in the European Union: a consumption-based approach *J. Cleaner Prod.* **236** 117535
[49] Wang Q, Jiang X-T, Ge S and Jiang R 2019 Is economic growth compatible with a reduction in CO_2 emissions? Empirical analysis of the United States *Resour. Conserv. Recycl.* **151** 104443

[50] Jiang J-J, Ye B, Zhou N and Zhang X-L 2019 Decoupling analysis and environmental Kuznets curve modelling of provincial-level CO_2 emissions and economic growth in China: a case study *J. Cleaner Prod.* **212** 1242–55
[51] Wang Q and Jiang R 2019 Is China's economic growth decoupled from carbon emissions? *J. Cleaner Prod.* **225** 1194–208
[52] Lei R, Feng S and Lauvaux T 2020 Country-scale trends in air pollution and fossil fuel CO_2 emissions during 2001–2018: confronting the roles of national policies and economic growth *Environ. Res. Lett.* **16** 014006
[53] Philippe Thunis M C, Cuvelier C, Guizzardi D, Alexander D M, Oreggioni G and Pisoni E 2021 Sensitivity of air quality modelling to different emission inventories: a case study over Europe *Atmos. Environ.* X **10** 100111
[54] Bergamaschi P *et al* 2018 Inverse modelling of European CH_4 emissions during 2006–2012 using different inverse models and reassessed atmospheric observations *Atmos. Chem. Phys.* **18** 901–20
[55] Oda T *et al* 2019 Errors and uncertainties in a gridded carbon dioxide emissions inventory *Mitigation Adapt. Strategies Global Change* **24** 1007–50
[56] Thunis P *et al* 2018 PM2.5 source allocation in European cities: a SHERPA modelling study *Atmos. Environ.* **187** 93–106