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Leaders or laggards in climate action? Assessing GHG trends and mitigation targets of global megacities

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Abstract

Urban areas account for between 71% and 76% of CO_2 emissions from global final energy use and between 67–76% of global energy use. The highest emitting 100 urban areas (defined as contiguous population clusters) account for 18% of the global greenhouse gas (GHG) emissions. To date there is no comprehensive study of megacities (10 million+ population) analysing their historic population, economic and emission patterns and contributions to global GHGs. A key challenge is that a majority of these megacities (33 out of 41) are located in developing countries, making it challenging to track their rapidly mounting emissions. In this research, we capitalize on recently released open-access datasets—the Global Human Settlements Database (R2019A) and the World Urbanization Prospects (2018) for analyzing megacity development and GHG trends, vis-à-vis the mitigation targets outlined in their climate action plans. We find that as leading political and economic centres in their nations, though most megacities have initiated climate action plans, the aggregate impact of megacities on global emissions is limited. Based on this evidence, we explore how rapidly growing megacities can hedgehop to effectively reduce their GHG emissions while urbanizing and developing economically.

1. Introduction

As recent climate research undoubtedly indicates, global warming of 1.5˚C and 2˚C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions occur in the coming decades [1, 2]. This challenge mandates rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems [3]. Urban areas account for between 71% and 76% of CO_2 emissions from global final energy use and between 67–76% of global energy use [4]. Many international frameworks like the Sustainable Development Goals [5], the Sendai Framework for Disaster Risk Reduction [6], Paris Climate Agreements [7], and the New Urban Agenda [8] require human settlements information to feed indicators to form the basis for an empirical-informed policy for global climate action.

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Studies on urban climate mitigation particularly offer robust regional insights into climate planning [9] that necessitate up-scaling for systematic review of global urban climate action plans (CAPs). In the last two-decades, a fair amount of groundwork has been set by urban emission studies, intensifying both in scale and scope [10]. These have largely focussed on preparing GHG accounts and mitigation policies for cities–individually and collectively. Some cities, like Toronto, New York, London, Barcelona, Tokyo, and Beijing, are disproportionally considered in studies of urban emissions and climate action [11]. In parallel, there are growing comparative studies between cities at the national or continental scale. For example, Brookings Institution [12] assessed the carbon footprint of the 100 largest metropolitan areas in the US considering highway transportation and energy consumption in residential buildings. In Europe, researchers evaluate and compare GHG emissions and climate plans of assorted European cities, samples ranging from 18 to 200 cities/city-regions [13–15]. Similarly, studies from South-Asia [16, 17] analyse GHG composition of prominent cities across India, Sri Lanka, Bangladesh & Nepal to demonstrate how certain urban spatial parameters like geo-physical location, settlement structure/organization and industrial landuse are strongly correlated with their GHGs.

A high-resolution gridded model demonstrates that 35% of the global GHGs are concentrated in 200 high-income cities and suburbs [18], 41 of these are located in countries with relatively low emissions [19]. This necessitates an in-depth analysis of global GHGs from megacities, i.e. cities with population over 10 million. Despite megacities hosting 626 million people in 2015 [20], there is no special assessment of their emission structures and progression over the years vis-à-vis the development trajectory. While some colleagues studied energy and material flows of 27 megacities [21], they put less attention into their GHG composition and trends. Meanwhile, few others concentrated on energy metabolism of megacities mainly in emerging economies [22]. One study investigated 274 cities worldwide and found 8 types of cities, sorted according to their GHG emission patterns, also exploring the prospective relevance of fuel pricing and urban planning for reducing GHG levels for 2050 [23]. Recently, a research tracked historical emission changes for 42 key world cities, though over two data points only [24]. In addition to the apparent deviation in urban focus (mainly targeting energy and transport sectors), there is deviation amongst different agencies in acknowledging which cities are considered megacities (elaborated in Section 3: Data and Methods) and so it is important that we consider all these definitional issues.

Moreover, the research scope of urban emissions studies is evolving, from mere GHG assessment and comparison to evaluating climate policies and actions. For instance, there has been a survey of climate change experiments in 100 world cities across all inhabited continents [25], as well as an investigation into how 885 EU cities [26] are combating climate change through local climate plans. In addition, there is plenty of grey literature from multilaterals, city networks, private companies and NGOs like the Covenant of Mayors, World Bank, UN-Habitat, ATKINS, IBM, ICLEI, Rockefeller Foundation, etc. documenting and disseminating best practices. As more and more cities perform GHG assessments, there are large variabilities and inconsistencies in methodologies inhibiting a transparent and comparative analysis [27], essentially because of input data, methods adopted and desired outputs [17]. A key methodological variation is on account of production-based or territorial emissions of a city as against consumption or footprint based assessment that extends beyond the city boundaries. In either case, any comparison of megacities should source reliable and consistent GHG data to draw historic trends and correlations with development indices.

Given the size, wealth and wherewithal, there are immense climate mitigation opportunities in developing megacities, yet vast fragmented literature of growing case studies, particularly in developing Asia and Africa largely remains underutilized for an exhaustive and mainstream policy application [18, 28, 29]. While global comparisons of city cases are sparse, often restricted by data unavailability, incomparability and sector-oriented inferences; open-access quantitative datasets released recently–in particular the World Urbanization Prospects [30] and Global Human Settlements (GHS) Database [20] that allow for systematic coding of urban development, energy and GHGs from 1970–2012, remain vastly unexplored to address certain crucial scientific and policy enquiries. For instance, some pointed queries include: How are megacity emissions evolving—are these expanding or shrinking? What are the specific drivers (population, affluence or technology), functions/ sectors significantly contributing (emission hotspots) in megacities and are these representative of their national circumstances? Secondly, emission data has not been utilized to interpret the qualitative data on mitigation strategies pursued under their urban climate policy. Here, we aim to systematically evaluate global megacity development and GHG trends, vis-à-vis the mitigation targets outlined in individual CAPs so as to reduce their GHG emissions while developing economically. In order to pursue this methodically, we first acknowledge the *state-of-the-art* literature on factors that influence or associate with urban GHGs (Section 2). We then adopt mixed methods (explained in Section 3) to analyze megacity development trends, emission compositions and their mutual correlations along with interpreting CAPs (section 4). We finally infer key findings and recommendations imperative to generate a more focused policy response for urban climate action and sustainable urbanization.

2. Factors associated with urban GHGs

The prevailing literature expounds how urban GHGs are related to several parameters including city size, urban growth, sectoral or emission specific contributions, developed vs. developing contexts and result of strategies ensuing climate action plans (CAPs). Unless otherwise mentioned, GHG in our study refers to territorial emissions emanating from a city. We review global literature to better decipher relevance of these parameters in context of global megacities.

2.1 Developed versus developing context

Global cities are a varied lot and their GHG emissions are influenced by economic and developmental status. For instance, cities in the Kyoto Protocol's Annex-I (developed) countries have lower per capita energy use and thus GHG emissions than national averages [4]. Analysis of 200+ countries/territories shows that GHGs demonstrate stronger correlation to their urbanization levels, than to their GDP [17]. How relevant is this to megacities as urban carbon GHGs are growing irrespective of their global 'North–South' disposition [31]? The development status becomes critical because there is robust evidence that the largest opportunities for future urban GHG mitigation are in developing countries where urban form and infrastructure are not locked-in, but often bear limited technical, financial, and institutional capacities to do so [4]. Thus it becomes vital to compare: (a) GHG structures of megacities at the continental level, and (b) Mitigation targets of individual megacities against their economic status.

2.2 City size

Several national-level studies indicate how the size of a city, both in terms of population and urbanized area is increasingly being associated with its GHG emissions. For e.g. production-based emissions from U.S. metropolitans during 1999–2008 demonstrate CO_2 emissions scale proportionally with city-population [32]. The analysis of the most populated Indian cities reveals that as the municipal area expands from 20 to 466 km^2, urban GHGs rise from 0.14 to 6.78 $MtCO_2e$, principally owing to a strong correlation ($R^2 = 0.77$) between city size and fuel emissions [17]. Is city size crucial in determining megacity GHGs too? The regression analysis of energy and material flows of 27 world megacities shows that their electricity use is significantly correlated with urbanized area [21]. Thus, contrary to general observation of urban emissions aggregating with city size, the key question is if larger cities (in terms of area or population) have proportionally larger or lower emissions? The general validity of how GHGs correlate with city size needs to be tested for both city population and urban area over a wide-ranged longitudinal data of global megacities.

2.3 Urban growth

A meta-analysis of 326 studies using remotely-sensed images demonstrates that urban land expansion rates are low and relatable to GDP growth in high-income countries [33]. Specifically, the annual growth in GDP/capita drives approximately half of the observed urban land expansion in China but moderately in India and Africa, where it is driven more by urban population growth. Nevertheless, the urban expansion rate is on average twice as fast as urban population growth [4]. A study utilizing fully convolutional network (FCN) to detect global urban expansion from 1992–2016 [34], concludes that the global urban land area increased 1.3 times from 274.7 to 621.1 thousand sq.km. Meanwhile, Landsat derived images of 13,000 urban centres from 1990–2014 [35] show average levels of greenness increasing in several cities. Greenness refers to the occurrence of green spaces within urban centres and has been produced by analysing Landsat annual reflectance composites values, ranging from 0.1 (barren land) to 0.9 (dense vegetation) [20]. A recent research synthesizing global trend of urban growth during 1970–2010 shows little horizontal expansion in large cities as against small and medium ones [36]. It thus needs to be ascertained whether megacities are driving the global urban growth?

2.4 Urban energy and transport

The emissions from global urban energy and transportation infrastructures are high, ranging 127–336 and 63–132 $GtCO_2$, respectively [4]. Data from 209 countries/ territories suggests that uncontrolled urbanization can spurt energy intensity (due to greater consumption of fuels and electricity), and hence lead to magnification of urban GHGs [17]. A study of four Chinese megacities (Beijing, Shanghai, Tianjin and Chongqing) quantifies and maps their carbon footprints indicating dominance of electricity-related emissions [37]. The urban form and structure significantly affect direct and indirect GHG emissions, and strongly linked to the throughput of materials and energy in a city, its waste generation and system efficiencies [4]. The energy metabolism in 27 global megacities, investigating mobile and stationary energy consumption, fuels and electricity generation mix, shows that compact cities are more energy efficient with respect to dispersed cities [22]. It further reveals that per capita energy consumption scales with a city's population density according to a power law characterized by the universal $-3/4$ scaling. Thus, the growth of transport infrastructure and ensuing urban forms have potential to affect long-run emissions trajectories in megacities, more so in developing nations.

2.5 Effectiveness of urban CAPs

Though thousands of cities are undertaking climate action plans, their aggregate impact on urban emissions is uncertain [4]. Local governments and institutions possess unique opportunities to engage in urban mitigation activities that are expanding rapidly [38]. However, there has been little systematic assessment regarding their strategic focus, extent of implementing mitigation measures and emission reduction targets or nationally determined commitments

(NDCs) actually being achieved. Secondly, beyond targets, the feasibility of spatial planning instruments for GHG mitigation is highly dependent on a city's financial and governance capability, expected to be most effective on bundling of actions and a high level of coordination across different agencies. The bundling could be both with adaptation strategies (like greening, cool roofs, urban forestry or agriculture, etc.) as well the ability to relate mitigation efforts to local co-benefits [39]. Urban co-benefits include public savings, air quality and associated health benefits, productivity improvements that further motivate expansion of mitigation activities [4]. But to what extent does a megacity's GHG mitigation potential depend on its financial means? Case study of individual megacities can help establish this in addition to evaluating climate actions for: (a) bundling of mitigation and adaptation strategies, and (b) coordination of synergies and co-benefits within the urban policy.

3. Data and methods

3.1 Megacity definition and sampling

The definition of a *megacity* includes all cities or urban agglomerations with 10,000,000+ population, yet there is no standard inventorization of world megacities. There are several agencies like Demographia, CityPopulation.de, UN DESA, etc. following different urban definitions and methods to list megacities, leading to different numbers. In order to have a thorough sample for our analysis, we include cities from all sources leading to a comprehensive list of 41 global megacities (S1 Annexure). Some cities within this list have population tending to 10 million in few years. For precision and consistency, we extract their population from a single, reliable and recent database i.e. *World Urbanization Prospects*: *The 2018 Revision* [30] that draws bottom-up data from countries. For built-up area, GDP and greenness of a megacity, we draw from GHS-UCDB: *The Global Human Settlement Layer Urban Centres Database*. Its version GLOBE R2019A V1.0 released in 2018 is the most comprehensive database for 10,000+ cities offering location, gridded population, urban-extent (surface, shape), geographical, socio-economic and environmental attributes, spanning 25–40 years [20].

3.2 GHG emissions data

In earlier urban energy/emission studies, some performed macroscale correlations (volumetric) and microscale correlations (per-capita) for energy-use [21] while some used similar approach of discerning urban GHGs as "spatial" or "direct", and "economic" or "life cycle based" emissions [40]. Essentially, the difference is about accounting production based/territorial megacity emissions attributed to cities or consumption based carbon footprints averaged to an individual (per-capita) basis. The latter includes extra-territorial emissions owing to importing/ exporting of goods, services, electricity, etc. and can vary considerably. The footprint assessment depends on data procurement from multiple exogenous sources and its collation poses a comparability challenge too. On the other hand, territorial-based accounting tracks emissions to the exact locations and activities of origin within the city concerned, thus being helpful in attributing accountability towards mitigation efforts. In order to have credible, consistent and comparable GHG dataset for sampled megacities, we draw from European Commission's in-house Emissions Database for Global Atmospheric Research (EDGAR v4.3.2), which estimates anthropogenic GHGs from 1970 to 2012, imputing it consistently over land area based on gridded population [41]. It includes CO_2, NOx, SO_2 from all production-based activities (except large scale biomass burning and land use, land-use change, and forestry) following standard sector definitions/codes, bottom-up approach of data computation and hence offering consistency and comparability [42]. The complete dataset of urban

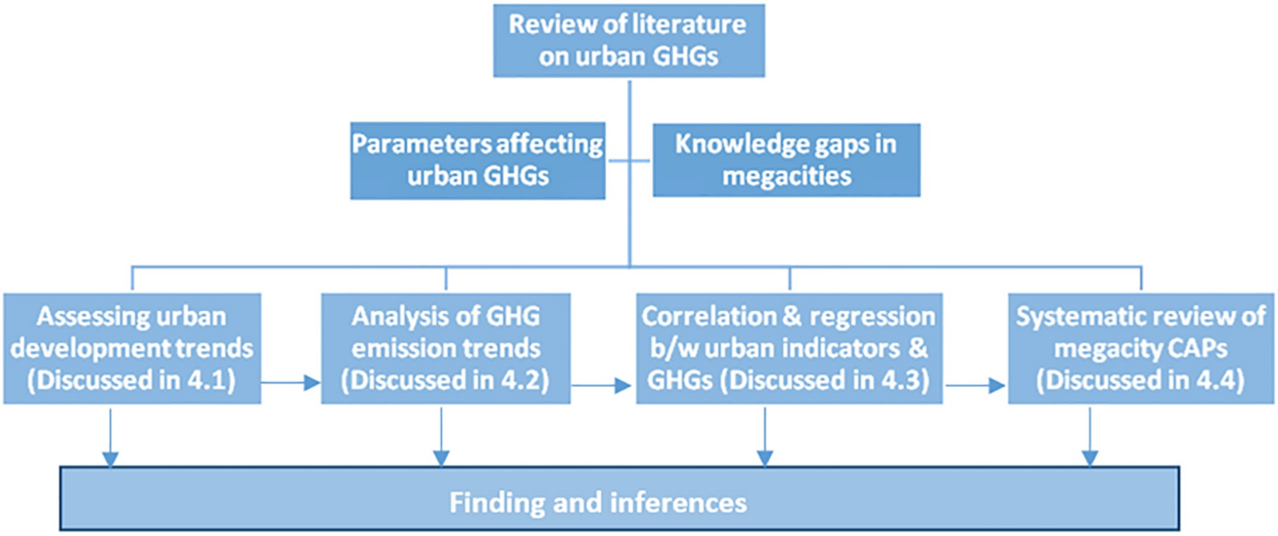

Fig 1. Upon identification of knowledge gaps and parameters affecting urban GHGs, the research methodology utilizes a mix of quantitative techniques (in analysing trends, correlations) and bibliometric/ systematic scoping techniques (in analysing urban CAPs).

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development and GHGs extracted for megacities is provided for 2012–15, 2000, 1990 & 1975 respectively in Tables A–D in S2 Annexure.

3.3 Methodology

Upon comprehensive review of literature studying urban emissions- factors affecting GHGs and knowledge gaps pertaining to megacities, our research utilizes both *quantitative analysis* and *qualitative analysis* broadly through the following four sequential processes (Fig 1): (1) Assessment of urban development trends in megacities, (2) Analysis of GHG emission patterns, (3) Deducing correlation between urban development and GHGs, (4) A comprehensive review of megacity CAPs, followed by interpretation of results to draw conclusions. The details of methods and techniques used in each process are provided in S3 Annexure. In nutshell, *quantitative analysis* of urban development trends and GHG emission pattern involves using compound annual growth rate (CAGR) method, their correlation entails multi-linear regression modelling (see S3 Annexure for intermittent steps), while review of megacity CAPs involves a systematic bibliometric review that builds on an ensemble of formal and rigorous methods in aggregating, reconciling and understanding evidence into discrete bodies of knowledge, guided by principles of reproducibility, transparency and justification of results [38]. We use *meta-synthesis techniques*, drawn from scoping studies [43–45] to prepare a Checklist for case study of megacity CAP (S4 Annexure) and an Inventory to code actions taken within the megacity CAPs (S5 Annexure). Upon basic training, the preliminary scoping and coding of megacity CAPs was carried out by an international team of 12 graduate students at the Technical University Berlin and the School of Planning & Architecture Delhi from November 2020 to June 2021. The queries during inventorization and coding included CO_2 or GHGs, focus on climate action, integrated landuse and transport (ILUT), transport and zoning regulations, financial investments in climate plan- local currency and year, waste to energy (WTE) projects. Upon primary review, a more comprehensive assessment of policy by the authors led to deducing final results.

4. Results

4.1 Urban development trends

4.1.1 Urban area and built-up area. During 1975–2015, the total physical/ geographical land area of the 41 megacities has almost doubled from 46,500 to 83,000 km^2, with average megacity area increasing from 1133 to 2027 km^2 (Table 1, for trend charts see Figs 2 & 4 in S6 Annexure). This urban expansion (μ = 1.5%) is led by megacities in Asia (2.14%), Africa (1.27%) and North America (0.95%) (see Table A in S7 Annexure for geographically classified data), notably by Bangalore (3.3%), Shanghai (3.5%), Tehran (3.6%), Dhaka (4.3%) and Xiamen (6.0%). The cumulative built-up area (BUA) of megacities grew 1.5 times from 29,783 to 43,697 km^2 and average built-up area per city from 726 to 1066 km^2. The growth rate in BUA is 1.0% annually, led by Asia (1.41%), North America (1.10%), Africa (1.01%) (Table A in S7 Annexure), highest in Lahore (4.2%), Shanghai & Hyderabad (3.0%), Bangalore (2.9%) and surprisingly, North American megacities exhibit growth rates of BUA exceeding urban area during this period, indicating greater vertical expansion than urban sprawl.

4.1.2 Population and density. During 1975–2015, world's megacities population doubled from 280 to 626 million, and average from 7 to 15 million per city at 2.0% annually. It is led by Asia (2.6%), in Xiamen (5.5%), Ho Chi Minh City (4.6%), Beijing (4.3%), Bangalore & Bangkok (4.2%), followed by Africa (2.4%), South America (1.8%), Europe (1.0%) and North America (0.7%). The population density (defined as population per km^2 of physical land) in world megacities (2015) varies considerably from Nagoya (2892 persons/ km^2) to Mumbai 20,200 (μ

Table 1. The average variation of key urban indicators and GHGs of 41 megacities.

	Data range	Average Value $_{base}$	Average Value $_{final}$	CAGR (in %)
Area (sq km)	1975–2015	1133	2027	1.5
Built-up Area (in sq km)	1975–2015	726	1066	1.0
Built-up Area/ capita (sq m/ capita)	1975–2015	117	71.96	-1.2
Population (persons)	1975–2015	6852350	15270225	2.0
Density (persons/ sq km)	1975–2015	7135	8960	0.6
GDP at Purchasing Power Parity (in USD)	1990–2015	106.92	231.97	3.1
Greenness (ratio)	1990–2014	0.42	0.45	0.2
Air quality (PM 2.5 ppm)	2000–2015	36.28	36.15	0.0
Total GHGs (MtCO$_2$)	1975–2012	1112.46	2566.02	2.3
Average GHGs/ city (MtCO$_2$)	1975–2012	27.13	62.58	2.3
GHGs/ capita (tCO$_2$)	1975–2012	3.85	3.84	-0.01
Average sectoral GHGs/ city				
Industry (MtCO$_2$)	1975–2012	14.14	32.18	2.2
Energy (MtCO$_2$)	1975–2012	4.41	14.71	3.3
Residential (MtCO$_2$)	1975–2012	7.30	11.30	1.2
Transport (MtCO$_2$)	1975–2012	1.22	4.27	3.4
Agricultural (MtCO$_2$)	1975–2012	0.04	0.09	2.1

Note: The indicators showing CAGR growth rates higher than the population growth are highlighted

Data Source:

1. Population data from *World Urbanization Prospects*: *The 2018 Revision* [30]
2. Built-up area, GDP, Greenness, Air quality data from GHS-UCDB: *The Global Human Settlement Layer Urban Centres Database* (version GLOBE R2019A V1.0) spanning from 1975–2015 [20, 35].
3. Total and sectoral GHGs from Emissions Database for Global Atmospheric Research spanning 1975–2012 [41].
4. Built-up Area/ capita, Density, Average GHGs per capita and per city, Average sectoral GHG/ city computed by authors.

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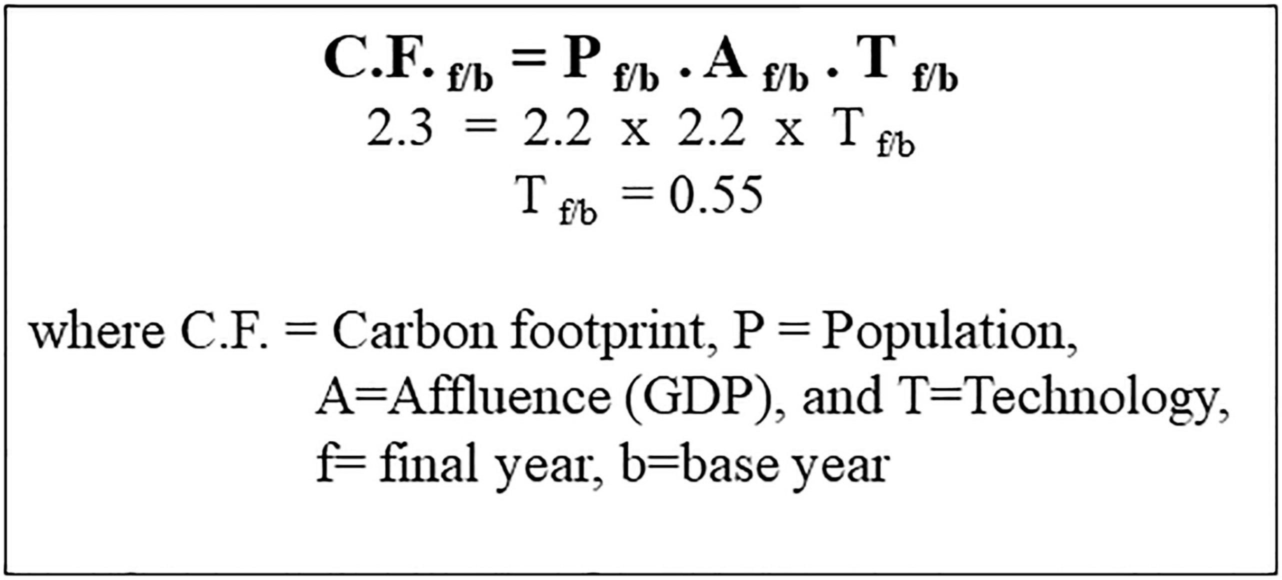
= 8960). From 1975–2015, the global megacities density grew from 7135 to 8960 at 0.6% annually (Table 1), varying considerably in North America (-0.23%), Asia (0.49%), Europe (0.59%) to South America (1.07%), Africa (1.11%) and Asia (2.64%) (see Table A in S7 Annexure), the highest being in Bogota (1.8%), Karachi, Beijing (1.9%) and Johannesburg (2.2%). Megacity densities are growing in all continents except North America, suggesting a *hollow urbanization* trend wherein megacities are expanding vertically (see 4.1.1. above) but with declining rates of habitation.

4.1.3 Gross Domestic Product (GDP). During 1990–2015, the cumulative GDP at Purchasing Power Parity of 41 megacities increased from USD 4.38 to 9.51 trillion (approximately China's GDP), the average megacity's GDP rising from USD 107 to 232 billion (Table 1). In 2015, it varied by a factor of 300 between Kinshasa (3.2) and Tokyo (1008) billion (μ = 101.81), for trend charts see Fig 6 in S6 Annexure). Similarly, income (USD/capita in 2015) varied by a factor of 80 from 574 (Kinshasa) to 42,352 (New York), μ = 15,191. While developed country megacities like London, Nagoya, Tokyo, Bangkok, Paris and New York (USD 27,000–42,000/capita) have the highest incomes, megacities from Asia (6.2%) and South America (3.6%) show above average (3.1%) growth rates during 1975–2015 (see Table A in S7 Annexure). There are two important observations: (a) With higher incomes and moderate growth, the European megacities, namely London, Paris and Moscow are in a sweet spot of economic sustenance, and (b) African megacities show an exceptionally lower economic growth (2.1%) than their population growth (2.4%) during this period.

4.1.4 Greenness. The data on green spaces (also called *greenness*) within urban centres has been produced by analysing Landsat annual Top-of-Atmosphere (TOA) reflectance composites available as collections in the Google Earth Engine (GEE) platform for the period 1990–2015. These composites are created by considering the highest value of the Normalized Difference Vegetation Index (NDVI) as the composite value [20], values ranging from 0.1 (barren land) to 0.9 (dense vegetation). In 2014, megacities showed a large range in greenness (μ = 0.31), ranging from Lima (0.15) to Guangzhou (0.5) closely followed by New York, Kolkata & Dhaka (0.49). The average megacity greenness increased from 0.42 (1990) to 0.46 (2010) and then declined to 0.45 (2015) with CAGR:0.2% (Table 1), with substantial increase in Istanbul, Mumbai & Mexico City (2%), Paris (1.8%), Hyderabad & Delhi (1.7%). From 1990–2014, megacities' greenness across continents (Table A in S7 Annexure) grew in South America (0.20%), Africa (0.44%), Asia (0.55%), while Europe (0.97%) and North America (1.15%) showed greater ecological sustenance. Interestingly, there are large variation within Asia amongst six Indian cities (1.49%), three Japanese cities (1.01%), 13 Chinese cities (-0.35%), while the remaining 10 Asian cities (0.53%), show rates quite close to Asia's average (for trend charts see Fig 7 in S6 Annexure).

4.1.5 Air Quality- particulate matter (PM) 2.5. In 2015, megacities show a large variation in air quality with PM2.5 levels ranging 12.91–110.00 (μ = 22.94). Megacities with the best air-quality are New York, London, Buenos Aires, Nagoya, Sao Paulo, as against worst ones in Asia; Delhi, Tianjin, Beijing Chengdu, Lahore, Dhaka and Shanghai. During 2000–15, a stark PM2.5 decline was seen in 23 cities, including Rio de Janeiro (-3.7%), Sao Paulo (-3.0%), Mexico City (-2.5%), Jakarta (-2.1%), though 18 cities showed sharp rise, notably Shantou & Cairo (1.0%), Bogota (1.2%), Chongqing (1.3%) and Guangzhou (1.5%). Does it have any connection with the city's greenness or transport GHGs needs to be verified through regression analysis. Geographically (Table A in S7 Annexure), the PM2.5 decline is typical to megacities of North America (-1.98%), South America (-1.51%), Africa (-0.21%), Europe (-0.16%), and counterbalanced in Asia (0.13%), essentially led by Chinese cities.

In addition to the growing population, *what are the major drivers of urban development and their GHGs*? The CAGR results (Table 1) show that economy (GDP) exhibits the maximum



$$C.F._{f/b} = P_{f/b} \cdot A_{f/b} \cdot T_{f/b}$$

$$2.3 = 2.2 \times 2.2 \times T_{f/b}$$

$$T_{f/b} = 0.55$$

where C.F. = Carbon footprint, P = Population,
A=Affluence (GDP), and T=Technology,
f= final year, b=base year

Fig 2. Longitudinal assessment of population, affluence and technological contributions to megacities carbon footprint.

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growth (3.1%), accompanied by increase of *urban area* (1.5%) and *built-up area* (1.0%) followed by greenness (0.2%). In fact, every one percent point of population growth is concomitant with 1.6 percent point increase in GDP, 1.15 in urban GHGs, 0.75 in urban area, 0.5 in built-up area, 0.3 in density and 0.1 in greenness. The 40-year data shows no perceptible change in air quality.

Secondly, *what drives GHG emissions rise in megacities*? Clearly, the emission growth in transport (3.4%) and energy (3.3%) surpasses the average: 2.3% (and population growth: 2.0%), while emission growth in industry (2.2%), agriculture (2.1%) and residential (1.2%) sectors lag behind. The longitudinal data assessment (Fig 2) shows that while population and affluence (GDP) both multiplied by a factor of 2.2 from 1975–2015, the GHGs grew by a factor of 2.3 during 1975–2012, indicating moderation by *technological efficiency* (a factor of 0.55) in megacities, a basic derivation based on [46]. A large body of literature on IPAT decomposition analysis and more sophisticated methods to quantify the contribution of population, affluence and technology [46–48] helps further establishing exact drivers of growth in emissions and their elasticities, which is otherwise outside the scope of this research and can be taken up for further investigation separately.

4.2 GHG emissions analysis

In this analysis, we cover the total megacity GHGs, their sectoral-breakup (industry, energy, residential, transport, agricultural) and their per-capita assessment:

4.2.1 Total GHGs. During 1975–2012, world's megacity GHGs increased from 1110 to 2570 $MtCO_2$. The latest available data (2012) shows World's megacity emissions (Fig 3) mounting by a factor of 129 (Fig 4), from 3.50 (Bogota) to 450 $MtCO_2$ (Shanghai) ($\mu = 27.95$ $MtCO_2$), for trend charts see Fig 1 in S8 Annexure). Geographically, average megacity GHGs are lowest in Africa (28.20 $MtCO_2$) and South America (30.52), doubling in Asia (70.52), Europe (70.89) and tripling in North America (91.96), see Table A in S7 Annexure. Meanwhile, GHGs of several developing country megacities; Shanghai (452 $MtCO_2$), Guangzhou (193), Bangkok (142) surpass developed megacities like Tokyo (241) or New York (141).

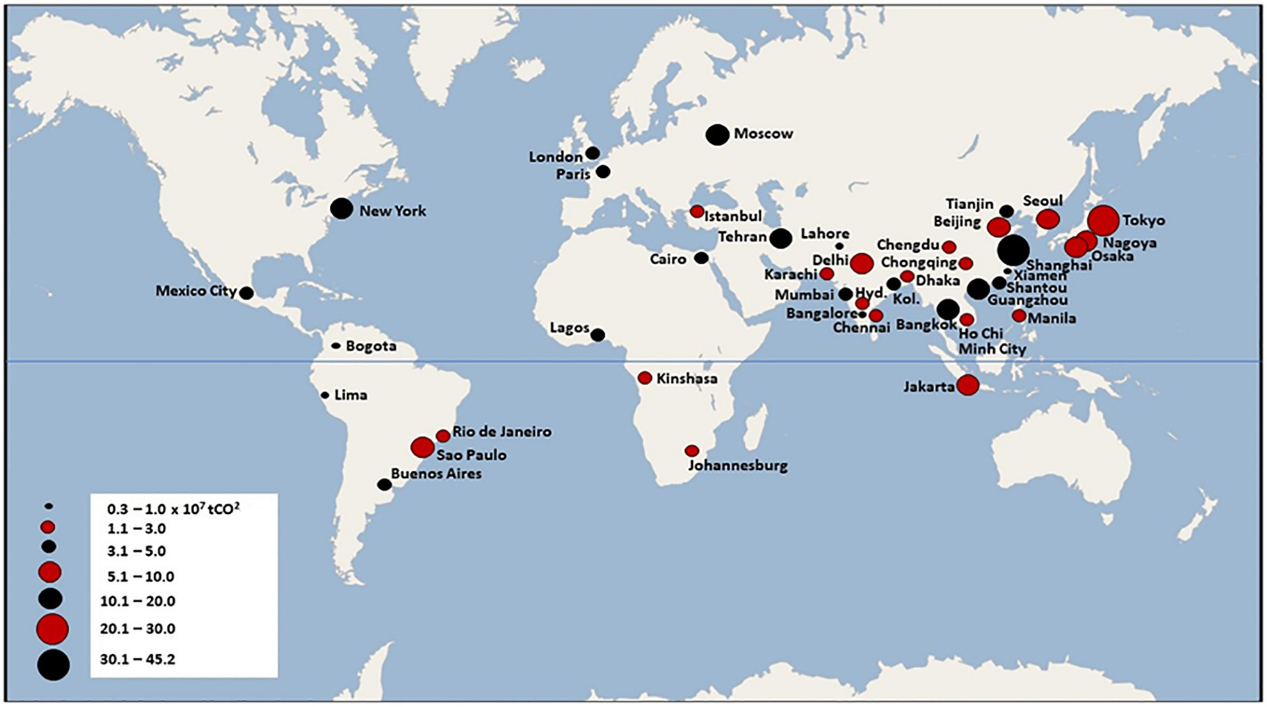

Fig 3. The carbon emissions (in 10^7 tCO_2) in 2012 plotted for 41 megacities across the globe. These vary considerably by a factor of 129, from an abysmal 3.50 (Bogota) to 451.73 (Shanghai), the mean being 27.95 $MtCO_2$. Image source: https://commons.wikimedia.org/wiki/File:World_map_blank_shorelines_semiwikimapia.svg, available under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

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During 1975–2012, megacity GHGs dwindled in Europe (-0.36%), inched in North America (0.45%), South America (1.55%) and enlarged in Africa (3.31%) and Asia (3.40%), the average climbing from 27.13 to 62.58 $MtCO_2$ (CAGR:2.3%), most prominently in Chennai (4.1%), Dhaka (4.7%), Cairo (5.1%), Guangzhou (6.0%) and Shanghai (6.2%).

4.2.2 Industrial emissions. During 1975–2012, industrial emissions from global megacities swelled from 580 to 1320 $MtCO_2$. In 2012, these varied by a factor of 270 (Fig 4), ranging from 1.40 (Bogota) to 378 $MtCO_2$ (Shanghai) ($\mu = 14.71$, half of total megacity GHGs 27.95 $MtCO_2$), for trend charts see Fig 7 in S8 Annexure. The average industrial emissions from megacities were low in Africa (15.25 $MtCO_2$), Europe (16.94), South America (22.11) but high in Asia (37.74) and North America (39.14), with Shanghai (377.86), Bangkok (122.32), Guangzhou (78.81), Tokyo (60.24), Sao Paulo (58.61) exhibiting major contributions. During 1975–2012, industrial GHGs changed gradually in megacities of Europe (-1.4%), North America (-0.1%), South America (1.6%) but rapidly in Africa (3.1%) and Asia (3.0%). The average megacity GHGs increased from 14.14 to 32.18 $MtCO_2$ (CAGR:2.2%), being negative and below 1% growth in Paris, New York, London, Moscow, Tokyo, Nagoya, Osaka, Manila, Lima to expeditious growth (5.4–6.7%) in Shanghai, Dhaka, Xiamen, Jakarta, Guangzhou and Tehran.

4.2.3 Energy emissions. During 1975–2012, energy emissions from megacities increased from 181–603 $MtCO_2$. In 2012, these varied by a factor of 109 (Fig 4), ranging from 1.13 $ktCO_2$ (Bogota) to 123 $MtCO_2$ (Tokyo), $\mu = 4.02$. There are 31 megacities less than the average, countered by a few guzzling ones like Tokyo (123 $MtCO_2$), Moscow (83), Guangzhou (78), Shanghai (47), Osaka (33). During 1975–2012, energy emissions grew significantly in

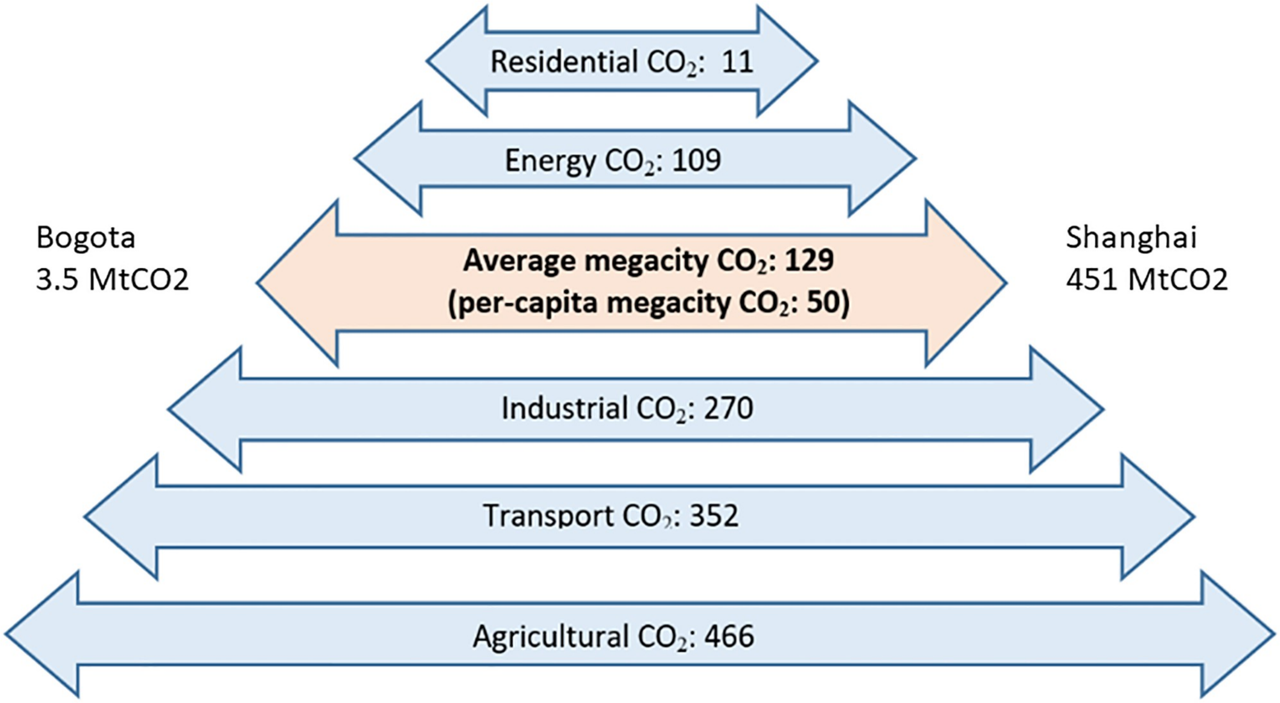

Fig 4. Average megacity CO_2 range by a factor of 129 between the maximal and minimal values, the residential emissions showing least variation while agricultural emissions showing the greatest range.

https://doi.org/10.1371/journal.pclm.0000113.g004

megacities of South America (4.9%) and Asia (6.6%) but declined in Europe (-2.3%) indicating greater utilization of renewables and perhaps an increasing displacement of energy intensive installations outside city boundaries. The average megacity energy emissions increased from 4.41–14.71 $MtCO_2$ (CAGR:3.3%), ranging from negative and below 1% growth rates in Paris, London, Kinshasa, Buenos Aires, New York to extremely high (10.2–13.7%) in Bangkok, Lima, Karachi, Jakarta and Lahore.

4.2.4 Residential emissions. During 1975–2012, megacities' residential emissions increased from 299–464 $MtCO_{2,}$ for trend charts see Fig 3 in S8 Annexure. For 2012, it was low in South America (4 $MtCO_2$), Africa (7) but high in Asia (11), Europe (20) and North America (28). It varied by a factor of 106 (Fig 4), from Xiamen (0.5 $MtCO_2$) to New York (49.32), $\mu = 4.45$ $MtCO_2$. There are 27 megacities with less than average GHGs as against largest contributors (16–49 $MtCO_2$) namely New York, Tokyo, Tehran, Seoul, Guangzhou, Moscow, Paris, Osaka, Jakarta and, Shanghai. The average residential emissions of a megacity hiked 7–11 $MtCO_2$ (CAGR:1.2%, interestingly half to population growth of 2.0%), ranging from negative to below 1% growth in Rio de Janeiro, Sao Paulo, Manila, New York, Paris, London, Lima, Bogota, Moscow and Mexico City to exponential growth (3.2–8.6%) in Tehran, Guangzhou, Kinshasa, Istanbul & Lahore, again largely associated with high population growth.

4.2.5 Transport emissions. During 1975–2012, megacities' transport emissions increased from 50–175 $MtCO_2$. In 2012, these varied by a factor of 352 (Fig 4), from Kinshasa (41 $ktCO_2$) to New York (14 $MtCO_2$), $\mu = 1.9$ $MtCO_2$. The transport emissions are low in megacities of Africa (2.4 $MtCO_2$), South America (2.8), Asia (4.3), but high in Europe (5.1) & North America (10.2), despite having most efficient metro transits. There are 26 below average

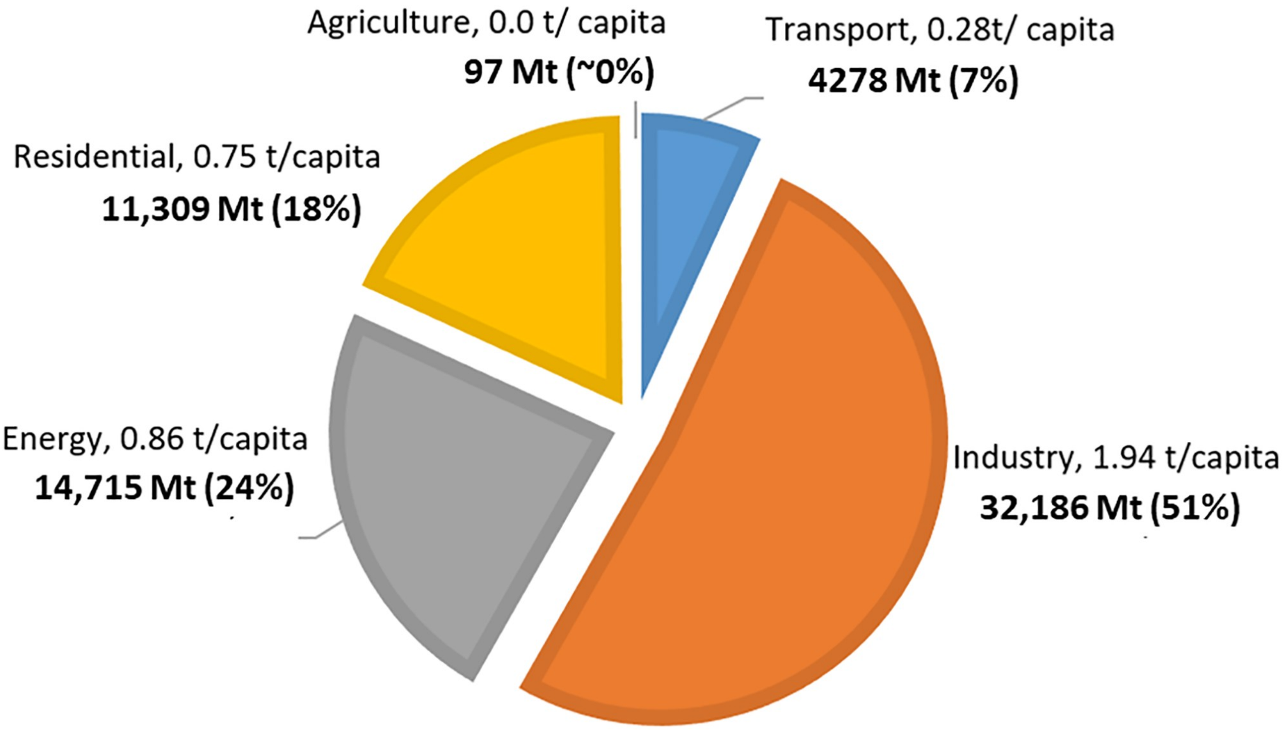

Fig 5. Sectoral composition of carbon emissions in global megacities (per-capita and total- with percentage contribution).

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megacities, mostly from Africa and India namely Kinshasa, Chennai, Bangalore and Hyderabad. Conversely, megacities with largest transport GHGs (9–14 $MtCO_2$) include New York, Jakarta, Guangzhou, Tokyo, Shanghai and Bangkok. The average megacity transport emissions increased from 1.22–4.27 $MtCO_2$ (CAGR: 3.4%), particularly high (7.0–7.7%) in East-Asian megacities of Shantou, Chongqing, Xiamen, Tianjin, Seoul, Chengdu & Guangzhou.

4.2.6 Agriculture emissions. The agriculture emissions are the lowest among all sectors. During 1975–2012, megacities' agricultural emissions increased from 1.8–4 $MtCO_{2,}$ for trend charts see Fig 8 in S8 Annexure. In 2012, these were lowest in Europe (0.002 $MtCO_2$), South America (0.003), Africa (0.008), North America (0.029) but extremely high in Asia (0.142), wherein megacities of Japan (0.009), China (0.012), India (0.092), contributed significantly less than the rest of the Asian cities (0.316). The agricultural emissions of global megacities vary astoundingly by a factor of 466 (Fig 4), ranging from 0.001 $MtCO_2$ (Lima) to 0.521 (Jakarta), $\mu = 0.012$ $MtCO_2$. There are 36 megacities with below average observations, but the largest ones (0.3–1.7 $MtCO_2$) include Jakarta, Ho Chi Minh City. Kolkata, Manila, Bangkok, all in Asia. A megacity's average agricultural emissions increased from 0.045–0.096 $MtCO_2$ (CAGR:2.1%) ranging from negative or below 1% growth rates in Moscow, Seoul, New York, London, Johannesburg, Istanbul, Paris and Tokyo to extremely high rates (4.4–5.0%) in Tehran, Beijing, Kinshasa, Cairo, Lahore and Lagos.

4.2.7 GHG emissions/ capita. In 2012, a megacity citizen's GHG emissions varied by a factor of 50 ranging 0.4–18 ($\mu = 2tCO_2$/capita). These are dominated by Industry (51%), followed by Energy (24%), Residential (18%), Transport (7%) and negligibly by Agricultural emissions (Fig 5). These are low in South America (2.2 tCO_2/capita), Africa (2.9), Asia (4), but considerably high in Europe (5.9) and North America (5.5) and three Japanese megacities- all exceeding 5.7 tCO_2/capita. Interestingly, the average megacity GHGs remained almost constant around 3.85 tCO_2 during 1975–2012. Continentally, megacities in Europe (-1.45%), South America (-0.37%), North America (-0.31%) show negative growth rates vis-a-vis Asia (0.54%) and Africa (0.70%). The negative growth in 15 megacities was counterbalanced by rapid growth (2%–3.8%) in select cities like Tehran, Guangzhou, Cairo and Chongqing.

4.3 Correlation and regression of GHGs with urban parameters

As explained in the methods (Section 3.3), GHGs (total and per-capita) of 41 megacities are correlated and regressed against the urban parameters for the most recent data (2012–2015) in a stepwise manner: (a) *Testing of strength*: parameters indicating moderate correlations ($0.40 \leq R^2 \leq 0.60$) to strong correlations ($R^2 > 0.60$), see Table A in S9 Annexure; (b) *Excluding outliers*: Shanghai, Dhaka, Guangzhou are omitted to assess corrected/ statistically significant values (Figs 6 & 7). The non-significant correlation charts are provided (see Figs 1–19 in S9 Annexure); (c) *Controlling of variables*: through ordinary least squares (OLS) multi-linear regression.

With respect to *city size and GHGs*, we report that these are reasonably associated (Fig 6), more in case of *urban area* ($R^2 = 0.70$) than *population* ($R^2 = 0.44$), see Table A in S9 Annexure. While comparing *developed versus developing megacities***, t**he association of total CO_2 emissions with GDP (Table A in S9 Annexure) shows a considerable degree of strength ($R^2 = 0.64$), in the sense that GHGs of richer cities are generally proportionally higher than economically developing ones, the exception being Bangkok, Shanghai and Guangzhou. The third query was about finding patterns between *city expansion (urban growth) and GHGs*. While urban areas are known to expand twice as fast as urban population growth [4], we found this trend to be relatively nuanced in megacities. While megacities population increased 2% annually, their urban area expanded moderately at 1.5% (see Fig 2). So, how do megacities hold the increasing population? The robust correlation between built-up area ($R^2 = 0.74$) with GHGs suggests that urban growth in megacities increasingly translates into vertical expansion. Probing the role of *urban energy and transport* further validates this assertion. We deduce that these functions not only consistently drive megacities' emissions growth during 1975–2012, but correlate significantly ($R^2 = 0.81$) to their GHGs through rising individual incomes (Fig 7). Conversely, Rio de Janeiro, Bogota and Istanbul exhibit low emissions despite higher incomes.

Upon preliminary regression analysis, we found that value of $R^2 = 0.56$, indicating that 56% of the variations in dependent variable (CO_2 emissions) are explained by the population, BUA, area, density, GDP and Greenness (results detailed in S10 Annexure). The p-value (5.84E-05) of F-statistic given in ANNOVA (Table B in S10 Annexure) is significant varying from 0.04 to 0.58 (Table C in S10 Annexure), yet p-value for the coefficients of Population (0.42), Area (0.399), Density (0.585), BUA (0.47) and Greenness (0.15) are all greater than 0.05 indicating that not all independent variables are statistically significant. We repeat regression analysis after eliminating higher p-value variables and select cities (Tehran, Shanghai, Jakarta, Dhaka and Moscow) displaying outlier values for certain variables, results tabulated in Tables D–F in S10 Annexure. Here, the R-squared value of 0.90 indicates that our model accounts for about 90% of the dependent variable (CO_2 emissions') variance by three key independent variables; GDP, Area and Greenness estimated through an exponential equation (Eq 1).

$$\begin{array}{lclllllll} Y & = & (-)13929497.3+ & 11318.5 & X_1+ & 0.00015 & X_2- & 17212723.3 & X_3 \\ \text{P value} & = & & (0.024772) & & (1.41E-06) & & (+0.00699) & \end{array} \tag{1}$$

where Y = Total carbon emission, X_1 = Area, X_2 = GDP, and X_3 = Greenness

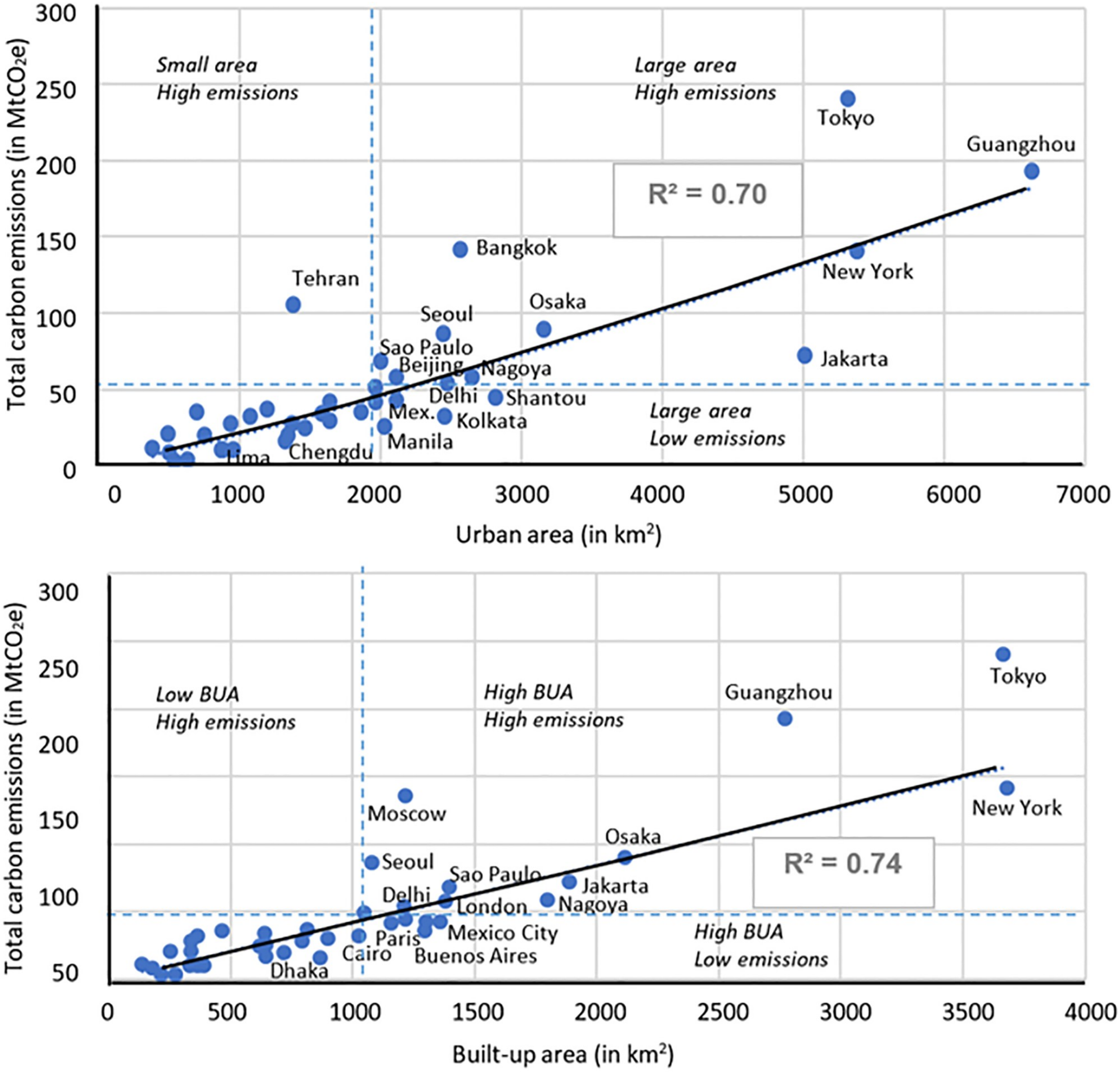

Fig 6. There is a strong correlation of megacity emissions with urban area and built-up area.

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4.4 Assessment of Megacity CAPs

As outlined in methodology (Section 3.3), quantitative assessment of megacities is supported by bibliometric analysis and meta-synthesis of their CAPs. Amongst 41 global megacities, 30 have specific CAPs out of which 24 are officially prepared or sponsored by their city authorities. For remaining 11 megacities, 7 conform either to their national or provincial CAPs. These were systematically assessed (S5 Annexure) leading to some new and interesting findings:

4.4.1 Myopic scope of urban boundary and gases. Out of 30 megacity CAPs, 10 pertain to municipal areas rather than entire metropolitan areas, thereby discounting GHGs from suburbs, peripheral areas and floating population. In fact, only three megacity CAPs (Buenos

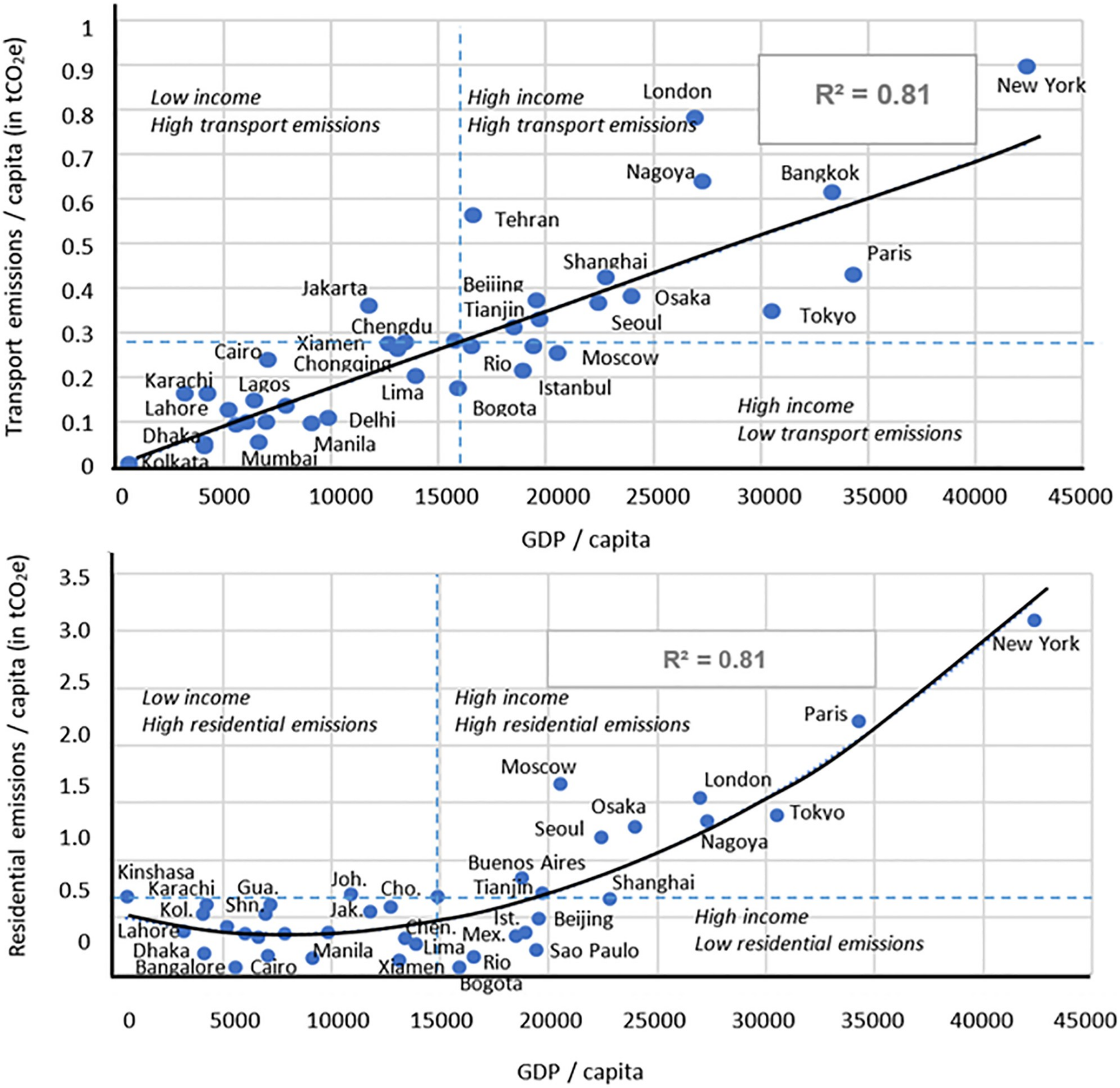

Fig 7. Megacity's per-capita emissions- transport and residential are strongly correlated with income.

https://doi.org/10.1371/journal.pclm.0000113.g007

Aires, Chengdu and Tokyo) consider daytime migration [49–51]. This is a *definition* cum *boundary* issue we dealt in our quantitative analysis by following the gridded population accounting method [20] that imputed population to 250x250m^2 grid scale, yet it demonstrates how the standard practice of considering megacity population in CAP can be limited in scope. Seven megacities still follow sub-national/ provincial CAPs and don't have a specific plan for their jurisdiction. In addition, not all megacities follow a standard inventory of gases: 22 account for GHGs, 10 for CO_2 and information is unavailable for 7. The accounting method is also non-standard i.e. some megacities account for primary energy (including industry, transport and electricity) while others collate, report and prepare plans separately for each of the sub-categories. In 17 CAPs (41%), reporting of industrial emissions and its mitigation is totally excluded.

4.4.2 Geographic peculiarities. Certain geographical patterns in CAPs is palpable, for instance the European, North American and Japanese megacities typically focus on GHG mitigation leading to net zero emissions. The residential emissions are extremely high in Japanese cities, 20.2 $MtCO_2e$ in Osaka and 10.3 MtCO2e in Nagoya and also for energy related GHGs, like 33.5 MtCO2e in Osaka and 31.5 in Nagoya [52, 53]. Most megacities (except Moscow & Japanese) have largely controlled their stationary emissions from coal-fired thermal and manufacturing plants within their territorial boundaries and now focussing on reducing transport, domestic and waste related emissions. As South-American cities are typically fed by hydroelectric and biofuels, their CAPs too show more focus on compact urban form and ILUT than greening energy sources [54–56]. Most Chinese megacity CAPs declare their high industrial emissions and commit to relocating factories beyond city-limits or shifting to natural gas and renewables. The electrification of city bus-systems is common here and WTE is being rapidly deployed, suggested by regional-level municipal waste studies too [57, 58]. In addition, most Chinese megacities have included adaptation strategies too. Meanwhile, Indian cities (except Delhi & Kolkata) have emission inventories but lack specific CAPs (see S5 Annexure), essentially following their state climate action plans. The SE Asian megacities have mitigation themes spanning multiple sectors (but none commit to achieving net-zero standards) while adaptation actions have been totally excluded (except Ho Chi Minh city). Climate planning in the rest of the Asian megacities like Tehran, Lahore, Karachi and Dhaka is either absent or lack sufficient rigour in outlining their actions. Similarly, in case of Africa, except Johannesburg, megacities have not prepared CAPs and follow state/ national climate plans. The developing country cities in Africa and Asia are most susceptible to global warming impacts and absence of urban adaptation/resilience plans is incomprehensible. Meanwhile, with increasing incidences of heat waves, forest fires and flooding in higher latitudes, it is paramount that industrialized and cold cities with more than 2000 heating degree days in 2011 [21] like Moscow, Paris, New York, Beijing, London, Seoul and Tokyo that traditionally focused on mitigation policies now urgently need to internalize resilience strategies in their urban policies.

4.4.3 Limited focus on sectors and targets. Despite megacities being economic powerhouse, leaders and influencers in the global order, their CAPs are quite inconsistent, in terms of focus on sectors/projects and planned targets to achieve those. For instance, 19 CAPs emphasize mitigation strategies while only 16 include both mitigation and adaptation pathways. Prominent cities like New York, Paris, London, Shanghai & Tokyo mention the need of adaptation and its alignment with mitigation objectives but do not outline specific adaptation strategies. While our assessment confirms that most city climate plans commonly focus on building energy efficiency and mass/bus rapid transit projects [4], we discern that their backstream or front-end linkages are not properly defined. For instance, there is often little emphasis on sourcing of energy from renewables or on generating co-benefits with pan-city ILUT or transit-oriented development projects and thus diminishing urban congestion and increasing active mobility. Only 23 cities out of 41 have planned climate mitigation targets (see Table A in S11 Annexure); as precise *GHG abatement volume* (in $MtCO_2$) in three megacities–Bangkok, Karachi, Xiamen to mainly having *percentage-based savings* on baseline emissions in 19 cities, while Mexico City has both. The percentage-based emission targets vary from 10% by 2020 to 100% i.e. net-zero emissions by 2050 for London, Paris, Seoul, Tokyo and by 2065 for Rio de Janeiro. Interestingly, the baseline emissions over which commitments are made also vary significantly from 9.75 $MtCO_2e$ (Bangkok) to above 200 $MtCO_2e$ for New York, Moscow and Shanghai. In order to compare climate targets, we converted the absolute emission reduction figures to percentage (except for Bangkok and Xiamen for which baseline year was unavailable). This shows that year-on-year GHG reduction target varies significantly from 1% (Manila, Johannesburg, New York and Tokyo) to 5% (Sao Paulo). In fact, most of these are trivial compared to their countries' NDCs annualized for 2030, viz. Philippines 7.5%, South Africa 1.9%, USA 2%, Japan 1.5% [59]. This is counter-intuitive to the claim that cities are harbingers of achieving the 1.5˚C climate target.

4.4.4 Wealth is necessary but not sufficient for urban climate action. Our analysis reasons how urban CAPs as a policy instrument are merely the first step in responding to climate change. Only 14 out of 41 (34%) megacities, namely Guangzhou, Shanghai, Hong Kong, Bangkok, Ho Chi Minh city, Osaka, Paris, Tokyo, Mexico City, Buenos Aires, Bogota, Rio de Janeiro, New York and London regularly keep a tab on their climate goals. Our analysis further reveals that the popular perception that a city's economic wealth has a bearing on its seriousness in devising climate goals shows it is a necessary but not sufficient condition (see Fig 1 in S11 Annexure). With no city below annual GDP of USD 7190/capita (Guangzhou) doing regular monitoring of CAPs indicates that the average annual GDP of megacities (USD 7647/capita) appears to be a threshold level of affluence (akin to environment Kuznets' Curve) when cities start tracking their climate goals. Meanwhile, rich cities like London, New York, Paris, Tokyo, Osaka, Bangkok, Shanghai, Buenos Aires, Mexico City, Rio de Janeiro, Bogota, etc. (annual GDP ranging between USD16,000 and 42,000/capita) keep strict and time-bound tracking of their CAPs, several other cities in this group like Tehran, Istanbul, Beijing, Sao Paulo, Tianjin, Moscow, Seoul, Nagoya have still not monitored progress of their earlier CAPs. Conversely, few moderately affluent cities; Guangzhou (USD 7190/capita/year), Ho Chi Minh City (USD 7858/capita/year) and Manila (USD 9118/capita/year) actively monitor their CAPs. This can perhaps be attributed to greater threat perception of global warming impacts like sea-rise in these coastal cities. This role of efficient municipal governance, their leadership, capability and willingness to take prompt decisions deserves further academic attention.

4.4.5 Non-definite and complex modes of governance. Megacities exhibit a complex system of urban management with overlapping and multi-tiered governance architecture. This is reflected in how CAPs attempt to pursue a mix of arrangements to combat climate change. First, the responsibilities are usually distributed amongst the municipal entity, metropolitan authority and the state/national government departments though the city governments are the direct stakeholders bearing administrative and financial dependence on supra-urban governments. As such, systemic projects like phasing out coal based national thermal plants, initiating rail-based mass rapid transit systems, utilizing public lands for green energy projects and afforestation requires persistent commitment from state/national governments. Secondly, most urban governments seem undecided on how to deal with industrial emissions in their jurisdictions (see S5 Annexure), perhaps weighing tax-profits at the cost of environmental pollution. The modes of governance vary considerably from showing ineptitude (Bangkok, Jakarta, Johannesburg, Karachi, Manila, Mexico City, Rio de Janeiro, Sao Paulo, Tehran) to strict regulations like penalization, closing down & relocation (Beijing, Chengdu) to providing incentives and sustainable ecosystems to cap GHG emissions (Tokyo). Some urban governments provide innovative and pro-active actions to engage with their employees and citizens like incentives for greener modes in employee commute in Moscow, provision of self-service bike-hire (Velib), car-hire (Autolib) and identifying climate ambassadors, student representatives and eco-manager professionals in Paris [60], incentivizing rooftop solar in homes and free travel on public transport for women in New Delhi [61]. At the same time, naïve strategies like maximizing coal output and managing coal-fired power stations in a carbon neutral way outlined in Dhaka's CAP [62] shows that developing megacities still need greater guidance and handholding to define their actions.

4.4.6 Effects of scaling. The role of urban scale is perhaps overemphasized when it comes to dealing with climate planning. While literature on urban scaling [32, 63, 64] associates greater economic productivity and thus mitigation potential with large cities, our results show that even while city size varies significantly, from 383 (Kinshasa) to 6622 km^2 (Guangzhou), it is not directly correlated with urban GHGs. In addition, the size of the problem does not bear any relation with or impacts on the climate ingenuity of these cities, as validated by supporting evidence from CAPs. For instance, climate plans of smaller cities are equally innovative and detailed in dealing with indigenous issues like methane capture from existing landfills (Shantou), control of per-capita floor space to save energy in buildings (Chengdu) or integrating transit with compact city form (Buenos Aires, Lima). It is vital that scientists and policy makers identify and propagate these multi-sectoral initiatives, especially in cash-strapped developing cities to combat global warming.

5. Conclusions and policy recommendations

As climate change intensifies, cities offer huge opportunities to address this crisis. Through this research, we wanted to ascertain how the most influential and affluent lot of global cities, i.e. megacities stand-up to this challenge. We used some unexploited data (precise historic emissions spanning 1975–2012) inventively combining statistical techniques (CAGR method), correlation and regression analysis and systematic case studies of megacity CAPs, in evaluating urban development and emission scenario. The research concludes with some interesting scientific findings and policy imperatives for world's largest urbanity:

5.1 Megacities are highly diverse

Despite having economic prowess in common, megacities are highly varied in not just urban parameters (urban area, density, BUA), geographic/ regional characteristics but also their GHG composition, including residential, industrial, energy, transport, agricultural. The study of CAPs further reveals the range of accounting methods, emission targets and climate policies adopted by different megacities. Thus, there should be further methodical research into megacities' energy-mix, their urbanization patterns, land development, transport, energy and ecological policies to draw comparative and city specific inferences for carbon-neutral development and urban resilience.

5.2 Key drivers and sources

There are some major drivers of urban development and GHGs. As results show, urban economy exhibits maximum growth (CAGR 3.1%), accompanied by an expansion of urban area (1.5%) and built-up area (1.0%). Secondly, every 1% rise in population is concomitant with increase of 1.6% GDP, 1.15% GHGs, 0.75% urban area, 0.5% built-up area and 0.3% density. In terms of source, the average megacities' emissions growth during 1975–2012 ($\mu = 2.3\%$) was essentially contributed by urban *transport* (3.4%) and *energy* (3.3%) sectors (significantly surpassing *population growth*: 2.0%), followed by *industry* (2.2%), *agriculture* (2.1%) and *residential* (1.2%) sectors. Amongst all the GHG accounting sectors, industrial, agricultural and transport sectors show the greatest variation between minimum and maximum CO_2 values for 41 megacities, indicating that much of the higher emissions in these sectors originate from select megacities (like Tokyo, Shanghai, Guangzhou, Bangkok) and hence controllable through pin-pointed intervention.

5.3 Hedgehopping—growing under the radar emissions

Highly emitting megacities like Tokyo, Guangzhou, New York, Bangkok, Osaka, Seoul, Nagoya, Jakarta, Shanghai, Tehran, and Moscow demonstrate undesirable pattern of urbanization. In fact, New York, Tokyo and Shanghai are the most intense emitters- peaking in all sector types, that compromises their overall environmental sustainability. A study attributes Shanghai as the megacity with worst environmental indicators [65]. On the other hand, African, South Asian, and Latin American cities with higher populations within lesser built-up areas present a low-carbon intensive i.e. relatively sustainable pattern of urbanization. There is a great challenge in managing the next stage of economic and infrastructural development for highly packed yet growing megacities like Jakarta, Bangkok and Dhaka. Fortunately, cities like Rio de Janeiro, Mexico City, Buenos Aires, Bogota and Istanbul exhibit higher incomes at the cost of lower GHGs/capita offering a 'hedgehopping' model of urban development, i.e. urbanizing under the emissions radar of 3.3 tCO_2e/capita.

5.4 Cohesive cities with green economies

There is strong association of GHGs with urban sprawl ($R^2 = 0.7$) in megacities too that refutes the usual claim that proactive management of peri-urban land is critical in small and medium cities only [36]. Chinese megacities have huge industrial and residential emissions sustained by importing energy from outside the city. In addition to curbing or transferring stationery emissions, these cities should focus on producing green energy themselves, adopting ILUT models of urban design like in Bogota [56] and utilizing waste to generate electricity. This can address the goal of improving environmental quality while sustaining economic development in China's megacities [66]. The decision makers, civic authorities, architects and urban planning communities should push for compact urban and peri-urban infrastructure development than indiscriminate sprawl through two key state-funded urban policies (a) *Infill development* for megacities with relatively thinner cores like Nagoya, Osaka and Johannesburg, and (b) *In-situ redevelopment* for megacities already hosting large population in dense slums like Mumbai, Lagos, Karachi, Dhaka. The projects should invariably mainstream climate strategies like solar-powered energy, green buildings, accessibility to metro line and job centres, waste composting and resilience to extreme events.

5.5 Systematic urban climate management

Our research demonstrates that effectiveness of CAPs is severely limited in mitigation targets, accounting of all emissions (particularly from industry, indirect and end-use energy), and lack of considerations towards co-benefits and integrated strategies. Out of 41 megacities, 16 CAPs include both mitigation and adaptation pathways, only 19 emphasize on mitigation strategies while bundling of sector strategies within these is even sparse. While urban prosperity (annual GDP beyond USD 7190/capita) generally translates into greater climate monitoring efforts to deal with climate challenge, several cities like Tehran, Istanbul, Beijing, Sao Paulo, Tianjin, Moscow, Seoul, Nagoya show limited progress in this regard. Thus cities can be planned and managed intelligibly, supported by scientific study of issues, goal-setting, clean technology selection and regular monitoring. Expanding the use of standard GHG inventories like by the World Resources Institute [67], etc. that include due classification of urban areas (municipality, city, metropolitan, megacity, etc.), defines all GHG emissions from varied sectors/activities particularly industrial ones, and consistent accounting methods by the international scientific community is imperative, so that largest emitting cities are systematically monitored for constructive policy action.

Supporting information

S1 Annexure. Sampling of 41 megacities.
(PDF)

S2 Annexure. Urban and GHG emission dataset of megacities.
(PDF)

S3 Annexure. Details of methods and techniques.
(PDF)

S4 Annexure. Checklist for case study of megacity CAP.
(PDF)

S5 Annexure. Data inventory for case study of megacity CAP.
(PDF)

S6 Annexure. Growth trends of key urban parameters.
(PDF)

S7 Annexure. Geographical patterns of megacity's average growth in urban variables and GHGs.
(PDF)

S8 Annexure. Growth trends of urban emissions (CO2e).
(PDF)

S9 Annexure. Results from correlations analysis.
(PDF)

S10 Annexure. Results from regression modelling.
(PDF)

S11 Annexure. Mitigation targets of megacities.
(PDF)

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Writing – original draft: Mahendra Sethi.

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References

1. IPCC. Summary for policymakers. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press; 2021.
2. UNEP. Summary for policymakers. Global environment outlook 6. 2019. https://www.unep.org/resources/assessment/global-environment-outlook-6-summary-policymakers?_ga=2.78860311.203974826.1653305568-1309466037.1637837841
3. IPCC. Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of. 2018 Oct 8;1(5).
4. Seto KC, Dhakal S, Bigio A, Blanco H, Delgado GC, Dewar D, et al. Human settlements, infrastructure and spatial planning. Cambridge University Press; 2014. https://pure.iiasa.ac.at/id/eprint/11114/1/ipcc_wg3_ar5_chapter12.pdf
5. UNDESA. Transforming our world: The 2030 agenda for sustainable development. New York: United Nations, Department of Economic and Social Affairs. 2015 Oct 21.
6. UNISDR. Sendai framework for disaster risk reduction 2015–2030. Geneva: United Nations International Strategy for Disaster Reduction; 2015.
7. UNFCCC. Paris Agreement. 2015. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf
8. UNGA. New urban agenda: Quito declaration on sustainable cities and human settlements for all (71/256). New York: United Nations General Assembly; 2016. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_71_256.pdf
9. Eisenack K, Roggero M. Many roads to Paris: Explaining urban climate action in 885 European cities. Glob Environ Change. 2022 Jan 1; 72:102439.
10. Creutzig F, Lohrey S, Bai X, Baklanov A, Dawson R, Dhakal S, et al. Upscaling urban data science for global climate solutions. Glob Sustain. 2019;2.
11. Lamb WF, Creutzig F, Callaghan MW, Minx JC. Learning about urban climate solutions from case studies. Nat Clim Chang. 2019 Apr; 9(4):279–87.
12. Brown M.A., Southworth F. and Sarzynski A. Shrinking the carbon footprint of metropolitan America (p. 1). Washington, DC: Brookings Institution; 2008.
13. Carney S, Green N, Wood R, Read R. Greenhouse gas emissions inventories for eighteen European regions, EU CO2 80/50 Project Stage 1: inventory formation. Greenhouse Gas Regional Inventory Protocol (GRIP), University of Manchester; 2009.
14. Baur AH, Thess M, Kleinschmit B, Creutzig F. Urban climate change mitigation in Europe: looking at and beyond the role of population density. J Urban Plan Dev. 2014 Mar 1; 140(1):04013003.
15. Reckien D, Flacke J, Dawson RJ, Heidrich O, Olazabal M, Foley A, et al. Climate change response in Europe: what's the reality? Analysis of adaptation and mitigation plans from 200 urban areas in 11 countries. Clim Change. 2014 Jan; 122(1):331–40.
16. ICLEI. Energy and carbon emissions profiles of 54 south Asian cities. New Delhi: British High Commission & ICLEI South Asia; 2009. https://e-lib.iclei.org/wp-content/uploads/2015/04/Energy-and-Carbon-Emissions-Profiles-for-54-South-Asian-Cities.pdf
17. Sethi M. Climate change and urban settlements: A spatial perspective of carbon footprint and beyond. Routledge; 2017 May 18.
18. Moran DD, Kanemoto K, Jiborn M, Wood R, Seto KC. Carbon Footprints Concentrated in Few Global Cities. 2017 May 1. Available at SSRN 2984473.
19. Moran D, Kanemoto K, Jiborn M, Wood R, Többen J, Seto KC. Carbon footprints of 13 000 cities. Environ Res Lett. 2018 Jun 19; 13(6):064041.

20. Florczyk AJ, Melchiorri M, Corbane C, Schiavina M, Maffenini M, Pesaresi M, et al. Description of the GHS urban centre database 2015. Public Release. 2019; 1:1–75. Available from https://publications.jrc.ec.europa.eu/repository/handle/JRC115586

21. Kennedy CA, Stewart I, Facchini A, Cersosimo I, Mele R, Chen B, et al. Energy and material flows of megacities. Proc Natl Acad Sci U S A. 2015 May 12; 112(19):5985–90. https://doi.org/10.1073/pnas.1504315112 PMID: 25918371

22. Facchini A, Kennedy C, Stewart I, Mele R. The energy metabolism of megacities. Appl Energy. 2017 Jan 15; 186:86–95.

23. Creutzig F, Baiocchi G, Bierkandt R, Pichler PP, Seto KC. Global typology of urban energy use and potentials for an urbanization mitigation wedge. Proc Natl Acad Sci U S A. 2015 May 19; 112(20):6283–8. https://doi.org/10.1073/pnas.1315545112 PMID: 25583508

24. Wei T, Wu J, Chen S. Keeping track of greenhouse gas emission reduction progress and targets in 167 cities worldwide. Front Sustain Cities. 2021 Jul 12; 3.

25. Broto VC, Bulkeley H. A survey of urban climate change experiments in 100 cities. Glob Environ Change. 2013 Feb 1; 23(1):92–102. https://doi.org/10.1016/j.gloenvcha.2012.07.005 PMID: 23805029

26. Reckien D, Salvia M, Heidrich O, Church JM, Pietrapertosa F, De Gregorio-Hurtado S, et al. How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28. J Clean Prod. 2018 Aug 1; 191:207–19.

27. Bader N, Bleischwitz R. Measuring urban greenhouse gas emissions: the challenge of comparability. SAPI EN. S. Surveys and Perspectives Integrating Environment and Society. 2009 Dec 15(2.3).

28. Lamb WF, Callaghan MW, Creutzig F, Khosla R, Minx JC. The literature landscape on 1.5 C climate change and cities. Curr Opin Environ Sustain. 2018 Feb 1; 30:26–34.

29. Sethi M. Co-benefits assessment tools and research gaps. In: Mainstreaming climate co-benefits in Indian cities. Singapore: Springer; 2018. pp. 47–73.

30. UN DESA. World urbanization prospects: The 2018 revision, methodology (Working paper no. ESA/P/WP.252). New York: United Nations Department of Economic and Social Affairs; 2018. https://population.un.org/wup/Publications/Files/WUP2018-Methodology.pdf

31. Sethi M, de Oliveira JP. From global 'North–South' to local 'Urban–Rural': A shifting paradigm in climate governance? Urban Clim. 2015 Dec 1; 14:529–43.

32. Fragkias M, Lobo J, Strumsky D, Seto KC. Does size matter? Scaling of CO2 emissions and US urban areas. PLoS One. 2013 Jun 4; 8(6):e64727. https://doi.org/10.1371/journal.pone.0064727 PMID: 23750213

33. Seto KC, Fragkias M, Güneralp B, Reilly MK. A meta-analysis of global urban land expansion. PloS One. 2011 Aug 18; 6(8):e23777. https://doi.org/10.1371/journal.pone.0023777 PMID: 21876770

34. He C, Liu Z, Gou S, Zhang Q, Zhang J, Xu L. Detecting global urban expansion over the last three decades using a fully convolutional network. Environ Res Lett. 2019 Mar 11; 14(3):034008.

35. Corbane C, Martino P, Panagiotis P, Aneta FJ, Michele M, Sergio F, et al. The grey-green divide: multi-temporal analysis of greenness across 10,000 urban centres derived from the Global Human Settlement Layer (GHSL). Int J Digit Earth. 2020 Jan 2; 13(1):101–18.

36. Güneralp B, Reba M, Hales BU, Wentz EA, Seto KC. Trends in urban land expansion, density, and land transitions from 1970 to 2010: a global synthesis. Environ Res Lett. 2020 Mar 20; 15(4):044015.

37. Chen S, Long H, Chen B, Feng K, Hubacek K. Urban carbon footprints across scale: Important considerations for choosing system boundaries. Appl Energy. 2020 Feb 1; 259:114201.

38. Sethi M, Lamb W, Minx J, Creutzig F. Climate change mitigation in cities: a systematic scoping of case studies. Environ Res Lett. 2020 Aug 26; 15(9):093008.

39. Solecki W, Seto KC, Balk D, Bigio A, Boone CG, Creutzig F, et al. A conceptual framework for an urban areas typology to integrate climate change mitigation and adaptation. Urban Clim. 2015 Dec 1; 14:116–37.

40. Lombardi M, Laiola E, Tricase C, Rana R. Assessing the urban carbon footprint: An overview. Environ Impact Assess Rev. 2017 Sep 1; 66:43–52.

41. Crippa M, Guizzardi D, Muntean M, Schaaf E, Dentener F, Van Aardenne JA, et al. Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4. 3.2. Earth Syst. Sci. Data. 2018 Oct 26; 10 (4):1987–2013.

42. Intergovernmental Panel on Climate Change, Houghton JT. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Greenhouse Gas Inventory Workbook. OECD; 1996.

43. Pawson R, Greenhalgh T, Harvey G, Walshe K. Realist review-a new method of systematic review designed for complex policy interventions. J Health Serv Res Policy. 2005 Jul; 10(1_suppl):21–34. https://doi.org/10.1258/1355819054308530 PMID: 16053581

44. Kastner M, Antony J, Soobiah C, Straus SE, Tricco AC. Conceptual recommendations for selecting the most appropriate knowledge synthesis method to answer research questions related to complex evidence. J Clin Epidemiol. 2016 May 1; 73:43–9. https://doi.org/10.1016/j.jclinepi.2015.11.022 PMID: 26912124

45. Rycroft-Malone J, McCormack B, Hutchinson AM, DeCorby K, Bucknall TK, Kent B, et al. Realist synthesis: illustrating the method for implementation research. Implement Sci. 2012 Dec; 7(1):1–0. https://doi.org/10.1186/1748-5908-7-33 PMID: 22515663

46. York R, Rosa EA, Dietz T. STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. Ecol Econ. 2003 Oct 1; 46(3):351–65.

47. Steinberger JK, Krausmann F, Getzner M, Schandl H, West J. Development and dematerialization: an international study. PloS One. 2013 Oct 21; 8(10):e70385. https://doi.org/10.1371/journal.pone.0070385 PMID: 24204555

48. Lamb WF, Steinberger JK, Bows-Larkin A, Peters GP, Roberts JT, Wood FR. Transitions in pathways of human development and carbon emissions. Environ Res Lett. 2014 Jan 15; 9(1):014011.

49. CIUDAD. Plan de acción de cambio climático 2020. PAÍS: Argentina: Ciudad de Buenos Aires; 2015. http://cdn2.buenosaires.gob.ar/espaciopublico/apra/pacc_2020.pdf

50. WRI. Study on Chengdu low carbon development blueprint. Washington, DC: World Resources Institute; 2014. https://wrirosscities.org/research/publication/study-chengdu-low-carbon-development-blueprint

51. TMG. Zero emission Tokyo strategy. Tokyo: Tokyo Metropolitan Government; 2019. https://www.kankyo.metro.tokyo.lg.jp/en/about_us/zero_emission_tokyo/strategy.files/Full-ver.ZE-strategy0311.pdf

52. Ryutaro M. Osaka city action plan for global warming countermeasures. Osaka City Government 11th high level seminar on sustainable cities; 2020. https://www.iges.or.jp/sites/default/files/inline-files/S2-4_Mr.%20Ryutaro%20Michigami_Osaka_city.pdf

53. Sugiyama N. Local climate policies in Japan: a case study of Nagoya city's strategy. In: Handbook of Sustainability Management. Singapore: World Scientific Publishing; 2012. Pp. 513–529.

54. Buenos Aires. Plan de acción Buenos Aires 2030. 2015. http://www.ecopuerto.com/Bicentenario/informes/CAMBCLIM.BSAS2030.pdf

55. de Janeiro, R. Climate change adaptation strategy for the city of Rio de Janeiro. 2016. http://www.centroclima.coppe.ufrj.br/images/Noticias/documentos/plano_de_adaptacao-ENG-FINAL.pdf

56. DSE- District secretary of the environment. District plan for disaster risk management and climate change for Bogotá DC 2018–2030. 2018. https://ambientebogota.gov.co/plan-distrital-de-gestion-del-riesgo-y-cambio-climatico-para-bogota-d.c.-2015-2050

57. Mani SK. WtE best practices and perspectives in Asia. In: Coelho ST, Pereira AS, Mani SK, Bouille DH, Stafford WH, Recalde MY, et al. editors. Municipal solid waste energy conversion in developing countries. Elsevier; 2020, Jan 1. pp. 147–184.

58. Themelis NJ, Ma W. Waste to energy (WTE) in China: from latecomer to front runner. Waste Dispos Sustain Energy. 2021 Dec; 3(4):267–74.

59. UNFCCC. NDC registry. 2022. http://www4.unfccc.int/ndcregistry/Pages/Home.aspx.

60. City of Paris. Paris climate action plan. City of Paris: Green parks and environment urban ecology agency. 2018. https://cdn.paris.fr/paris/2019/07/24/1a706797eac9982aec6b767c56449240.pdf

61. GNCTD. Delhi state action plan on climate change. 2017. GNCTD & MOEFCC. http://moef.gov.in/wp-content/uploads/2017/08/Delhi-State-Action-Plan-on-Cimate-Change.pdf

62. MOEF. Bangladesh climate change strategy and action plan. Dhaka: Ministry of environment and forests, Government of the people's republic of Bangladesh; 2009.

63. Bettencourt LM. The origins of scaling in cities. Science. 2013 Jun 21; 340(6139):1438–41. https://doi.org/10.1126/science.1235823 PMID: 23788793

64. Lobo J, Bettencourt LM, Strumsky D, West GB. Urban scaling and the production function for cities. PLoS One. 2013 Mar 27; 8(3):e58407. https://doi.org/10.1371/journal.pone.0058407 PMID: 23544042

65. Shmelev SE, Shmeleva IA. Multidimensional sustainability benchmarking for smart megacities. Cities. 2019 Sep 1; 92:134–63.

66. Huang L, Yan L, Wu J. Assessing urban sustainability of Chinese megacities: 35 years after the economic reform and open-door policy. Landsc Urban Plan. 2016 Jan 1; 145:57–70.

67. WRI- WRI/WBCSD, ICLEI, C40, [Fong WK, Sotos M, Doust M, Schultz S, Marques A, et al.]. Global protocol for community-scale greenhouse gas inventories. 2021. https://files.wri.org/d8/s3fs-public/global_protocol_for_community_scale_greenhouse_gas_emissions_inventory_executive_summary.pdf