How do Urban Carbon dioxide Emissions, Urban Scale and Population Density relate to each other? - a literature based discovery

Santosh Kumar[1,2] and Roshmi Sen[1]

[1]National Institute of Technology, Rourkela, India, [2]Department of Planning, Odisha University of Technology and Research Bhubaneswar, India.

Abstract *In this study we explore the question whether urbanization promotes or mitigates climate change through review of prevalent empirical research that have been performed by employing various statistical and econometric models, such as-power law, urban kaya scaling and production function based models. Our study explains the strength and weaknesses of these models along with their limitations and constraints. As urban areas around the world are looking for carbon neutrality, future works based upon findings of this study would be potentially insightful in aligning the development trajectory of sustainable urbanization with economies of scale in CO2 emission of urban areas.*

Introduction

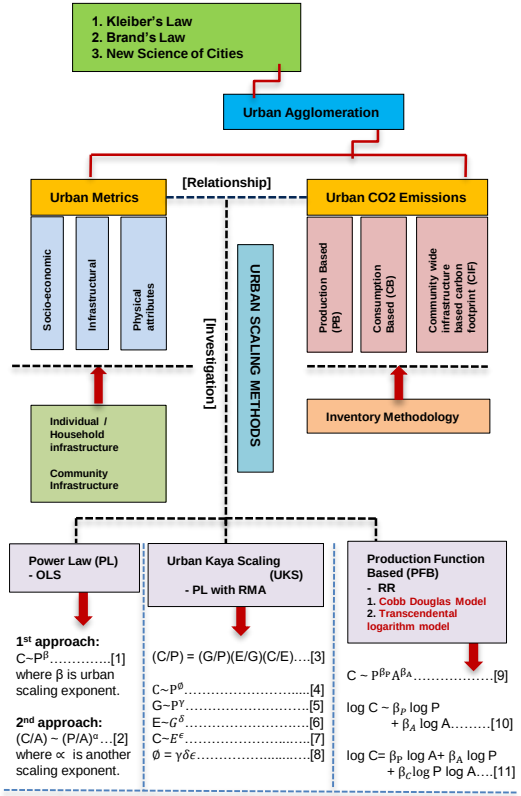
Carbon dioxide (CO_2) emissions are considered as one of the main reasons contributing to earth's climate change (Schellnhuber H. J. et al., 2006). It is well established from various sources that urban areas consume between 67 - 76% of the global energy supply and release 71-76% of the CO_2 emissions (Seto K. et al., 2014). It has been also witnessed that due to rapid global urbanization, the number and size of urban areas are increasing. This fact assigns urban areas a pivotal role in providing solutions and mitigation strategies towards global climate change problems. Consequently, sustainable management of urban areas is considered to be one of the main challenges of the 21st century. Researchers from several disciplines have investigated the effects of urbanization on CO_2 emissions. In this study, urban population size and population density have been considered as investigating parameters for identifying their relationships with CO_2 emissions by raising two pertinent research questions- first, *how urban population size relates to CO_2 emissions?* Second, *how does population density affect CO_2 emissions per capita at urban scale?* The goal is to understand urban-scale CO_2 emission and how they vary between urban areas with different densities.

Literature Review

Review step	Information gathered
[A] **Search of Database** Scopus Database	1. Year, 2. Title, 3. Journal , 4. Author , 5. Abstract
[B] **Content Assessment**	Objective of the Article / Answer should be yes for either of the following two questions
•Does the study explored the relationship between population size and urban C02 emissions / other urban metrics ?	
•Does the study explored the relationship between population density and urban C02 emissions per capita / other urban metrics ?	
[C] **Data Extraction**	1. Main objective 2. Country of the Study 3. Urban C02 emission method 4. Data type used in the study 5. Methodology / Tools / Techniques 6. Findings of the Study 7. Constraints / Limitations

Figure 1: Review Process

Conceptual Genesis of Urban Scaling



OLS: Ordinary Least Square regression; RMA: Reduced Major Axis regression; RR: Ridge Regression

C- CO_2 emissions; P- population; A- area; G- GDP; E - energy consumption

Figure 2: Review outcome flowchart

Overview of Selected Literature

Table 1: Articles selected from the literature review

PL — UKS — PFB

Authors' Year	Country/ EAM	Urban Units	Database/Year	Studied Urban Metrics
Bettencourt et al. (2007)	USA, EU and CHINA / NA	MSA, LUZ and UAU	U.S. Census Bureau,Eurostat Urban Audit,China's National Bureau of Statistics _1990-2003	Population size vs. Metropolitan infrastructure (MI), Individual needs(IN) and Social indicators (SI)
Glaeser et al. (2010)	USA / NA	MSA	National Household Travel Survey_2001	Population size Vs. gasoline consumption
Bettencourt et al. (2013)	USA / NA	MSA	Federal Highway Administration_2006	Population size Vs. Total road length
			U.S. Bureau of Economic Analysis_2006	Population size Vs. GDP of MSA
Fragkias et al. (2013)	USA / PB	MSA+ MA= (CBSA)	Vulkan Project_1999-2008	Population size Vs. CO_2 emissions
Oliveira et al. (2014)	USA / PB	MSA/CCA	Vuulkan Project, GRUMPv1	Population size Vs. CO2 Emission
Louf and Barthelemy (2014)	USA / NA	MSA	Census Bureau, Urban mobility Report, Federal Highway Administration	Population size Vs. excess C02 Emission per capita from congestion.
	OECD Countries / NA			Population size Vs. C02 Emission per capita from transportation.
Louf and Barthelemy (2014)	USA / PB	Urban Area MSA	Census Bureau, Vuulkan Project, GRUMPv1	Population size Vs. CO2 emissions
Horta et al. (2015)	Spain / NA	Towns and Cities	Google Public Data Explorer_2002_04_06_08	Population size Vs. Electrical energy consumption
Mohajeri et al. (2015)	Great Britain / NA	Cities	United Kingdom Office for National Statistics	Population size Vs. Land area Population size Vs. Street length Population size Vs. Number of streets Population size Vs. Transport fuel consumption Population size Vs. Transport C02 Emission
Gudipudi et al. (2016)	USA / PB	CCA	GRUMP, GLC, Vulcan project, NMM County Database (NCD)_2002 (Mobile 6.2 combustion emission) Model)	Population density Vs. C02 emissions per capita (on road + building)
Gudipudi et al. (2019)	Global cities (from Developed_Annex-1 & Developing_Non-Annex-1 countries as per UNFCCC framework) / PB	City	Global Energy Assessment, ICLEI,CDP & C40 Cities	Population size Vs. Emissions Population size Vs.GDP Energy Vs.GDP Emission Vs. Energy Population size Vs. Emissions Population size Vs.GDP Energy Vs.GDP Emission Vs. Energy Population size Vs. Emissions Population size Vs.GDP Energy Vs.GDP Emission Vs. Energy
Cheng et al. (2022)	China / PB	City (megalopolis, metropolis, large cities and middle & small cities.)	Intergovernmental Panel on Climate Change (IPCC) territorial emissions, CEADS database, China City Statistical Yearbook (2001~2017),	Population size Vs. CO2 Emission
Haroldo V.R. et al. (2019)	USA / PB	CCA	GRUMP, GLC, Vulcan project, NMM County Database (NCD)_2002 (Mobile 6.2 combustion emission) Model)	Population density Vs. C02 emissions per capita (on road + building)

MSA; Metropolitan statistical Area; MA; Micropolitan Area; LUZ; Large Urban Zone; UAU; Urban Administrative Unit ; CBSA: Core Based Statistical Area; CCA: City Clustering Algorithm; GRUMP: Global Rural-Urban Mapping Project; GLC: Global Land Cover Dataset; CEADS: Carbon Emission Account and Dataset; NMIM: National Mobile Inventory Model; NCD: National Country Database; PB: Production Based; EAM: Emission Accounting Method;; PFB; production Function Based; UKS: Urban Kaya Scaling; PL: Power Law; NA; Not Available

Discussion

After reviewing various research articles, it is found that there has been no scientific consensus on emission scaling approaches with population size or population density. The different urban metrics investigated can be segregated into three different baskets leading to the results shown in **Table-2**. The production function based approach was tested only for US cities, which demonstrated that the larger the city, the greater is the impact of changing its population or density on its emissions; but population changes was observed to always having a greater effect on emissions than population density (Ribeiro H.V. et al., 2019). The inconsistency shown in the outcomes of urban scaling approach for various reviewed articles can be attributed to multifold limitations and constraints.

Table 2: Urban Scaling Result

Approach	Urban Metrics	Remarks on Emission Scaling
PL (OLS) + UKS (PL with RMA)	A. Socio-economic :	Super- linear
	B. Infrastructure	
	i. Community :	Super-linear / Sub-linear / Linear
	ii. Household / Individual :	Super-linear
PFB (RR)	Physical Attributes	$Z^* = PA$
	Population, Area (P, A)	If $Z>Z^*$, Super-linear
		If $Z<Z^*$, Sub-linear

OLS: Ordinary Least Square regression; RMA: Reduced Major Axis regression; RR: Ridge Regression, Z^* refers to threshold value of density

Limitations/ Constraints in existing state of art

- ***Inappropriate emission accounting method:*** Due to limited data availability, most urban scaling studies consider only production based emissions, inhibiting our capacity to analyze the total carbon footprint and its relationship with Population size or density **.**
- ***Inability to explain underlying parameters of urban scaling***: Power law approach is unable to explain the underlying systematic dynamics that govern these scaling properties.
- ***Localized case study***: Power law scaling is limited to the urban system within a given country and fails to give global overview.
- ***Unexplained part of Urban Kaya Scaling:*** UKS approach fails to consider as government efficiency, trade and FDI.
- ***Absence of economic parameters in Production Function Based model:*** The PFB model doesn't consider factors (economic activity / technology / individual attitudes) which must be taken in to account while modeling carbon emission.
- ***Delineation of Urban Boundary difficult:*** Most reviewed studies undergo delineation problems of urban boundary because it incorporates total population that lies within urban limit without differentiating between rural part contained inside it.

Selected references:

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