Metropolitan Areas and CO_2 Emissions: Large is Beautiful

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Prepared by:

José Lobo, Ph.D, Arizona State University

Deborah Strumsky, Ph.D, University of North Carolina

Luis Bettencourt, Ph.D, Los Alamos National Laboratory

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The challenges of resuscitating the U.S. economy, developing new sources of economic prosperity, and addressing the causes and consequences of climate change, all intersect in the same physical space, namely metropolitan areas. The U.S. economy in effect consists of a diverse set of 366 metropolitan economies—distinct labor markets, agglomerations of individuals and households, centers of business activity, and hubs of innovation. The metropolitan economies of the continental United States cover only 29% of the country's land mass but house 84% of the nation's population and produce 93% of its output. Undoubtedly, the economic recovery of the United States and the future of its economy will be forged in metropolitan areas..

As citizens, policy-makers, academics, and business leaders imagine and debate what urban life must be like in order to create wealth in ways that are environmentally sustainable, the discussion should be informed by an understanding of the current environmental and energy implications of metropolitan areas. Many associate cities, and in particular large cities, with rampant consumerism, sprawl, traffic congestion, crime, and pollution. Yet ecologists have noted that by virtue of concentrating population in small areas, large cities can actually benefit the environment by decreasing human encroachment of natural habitats (*1*). Straightforward thermodynamic considerations lead to the realization that large apartment buildings are the most efficient dwellings to heat and cool. And economists have estimated that urban households in the United States emit less carbon dioxide than their suburban counterparts (*2*), and that city dwellers emit less CO_2 than residents of rural areas and small-towns (*3*). Quantifying the metabolic nature of metropolitan areas can help clarify whether large metropolitan areas pose a challenge to sustainability or constitute an important part of a sustainable future. Reliable data on the energy consumed in urban areas is, unfortunately, very sparse. Newly available data on CO_2

emissions, a widely used proxy for energy consumption, coupled with an analytical framework common in the natural sciences, allows us to identify the relationship between metropolitan size and energy consumption.

The Vulcan Project—funded by NASA and Department of Energy, and involving researchers from Purdue University, Colorado State University and Lawrence Berkeley National Laboratory—has measured, at a fine-grained spatial scale, North American fossil fuel carbon dioxide (CO_2) emissions generated in workplaces, power plants, roadways and residential areas (*4*). The project's reported data for 2002 fossil fuel CO_2 emissions in U.S. counties, measured in millions of metric tons, can be aggregated to construct measures of metropolitan CO2 emissions (the metropolitan "Carbon footprint"). The date is convenient for our purposes since we want to measure the Carbon footprint before the economic meltdown, catching metropolitan areas at their most debt-intoxicated, real estate-crazed and SUV-bloated behavior. With this metric in hand we can inquire as to how the size of metropolitan areas affects their use of energy (generated using fossil-fuels) utilizing *scaling analysis*.

Important properties of many physical and biological systems depend crucially on the size (measured as the number of constituent units) of the system, and scaling analysis seeks to uncover and quantify this relationship. The scaling relationship can often be mathematically represented through the simple equation

$$Y = cN^{\beta}, \quad (1)$$

with c a constant and the scaling exponent, β, determining how system size (N) affects systemic performance (Y). The presence of a scaling relationship implies "self-similarity" across different sizes or scales: if, for example, the rate of patenting occurring in cities is a function of urban size, then the number of new patents generated by a metropolitan area of 10 million inhabitants will stand in the same proportion to those generated by a city of one million, which in turn stands in the same relation to the number of patents generated by a city of 100,000, and so on. Scaling analysis has recently and fruitfully been applied to the study of various urban phenomena (*4-6*).

Metropolitan size can be measured either with respect to population or economic output, using Gross Metropolitan Product (GMP, the metropolitan equivalent of GDP).[1] In order to find what the scaling coefficient is, the basic scaling equation is transformed into the equation of a line by taking the natural log of both sizes of the equal sign:

$$\ln(Y) = c' + \beta \ln(N). \tag{2}$$

Using the available data and performing OLS regression (with a correction for heteroskedasticity) we can obtain an estimate of β. The results are shown in the two scatter plots below.

The measure of metropolitan carbon emissions used here includes emissions from commercial, industrial, residential and transportation energy usage occurring within metropolitan boundaries. Although the data from the Vulcan Project also includes carbon dioxide emissions generated from utility plants these emissions are excluded from the measure of metropolitan CO2 emissions used in this study. The reason for the exclusion is that in the U.S. the location of utility plants is determined as much by a maze of political, regulatory and tax considerations, at the State and county-levels, than by economic ones. Therefore the location of utility plants does not simply reflect demand considerations. Furthermore, utility plants often serve populations far away. Therefore the measure of metropolitan emissions includes activities that more or less directly reflect population size.

[1] Data for both is made available by the U.S. Department of commerce's Bureau of Economic Analysis (7).

Figure 1 depicts the relationship between metropolitan carbon emissions and population size, while Figure 2 shows the relationship between metropolitan carbon emissions and Gross Metropolitan Product. Both plots use data for the 360 metropolitan statistical areas (MSAs) in the continental United States.[2] Not surprisingly, the total amount of CO_2 emissions increase with metropolitan size—although the high r-square values suggest that metropolitan size is an important determinant of metropolitan carbon footprint. The scaling (or regression) coefficients tell an interesting story though.

When using population to measure metropolitan size, the coefficient of 0.92 indicates that the effect on total carbon emissions of increasing population size is slightly less than proportional: more precisely, a 1% increase in population is associated with a 0.92% increase in carbon emissions. When using economic output to measure metropolitan size, the scaling coefficient is 0.79, which means that a 1% increase in economic output is associated with only a 0.79% increase in CO_2 emissions. Together these two results tell us that larger metropolitan areas are indeed more energy efficient than smaller metropolitan areas—and in particular that increasing metropolitan wealth (as measured by GMP) is associated with decreasing energy consumption. The energy metabolism of metropolitan areas *slows down* with increasing size.[3]

[2] The boundaries of MSAs are defined by the U.S. Office of Management and Budget and are standardized county-based areas having at least one urbanized area with at least 50,000 inhabitants, plus adjacent territory that has a high degree of social and economic integration with the core, as measured by commuting ties. MSAs are, in effect, unified labor markets.

[3] In this respect urban areas are similar to biological organisms.

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4. The project's web site is at www.purdue.edu/eas/carbon/vulcan/index.php. The methodology used to measure CO_2 is explained in a forthcoming article in *Environmental Science & Technology* (http://www.purdue.edu/eas/carbon/vulcan/Gurney.EST.2009.pdf).

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8. For data on metropolitan population go to www.bea.gov/regional/reis/ and for Gross Metropolitan Product go to www.bea.gov/regional/gdpmetro/.

Figure 1. Scaling of metropolitan carbon emissions with population size.

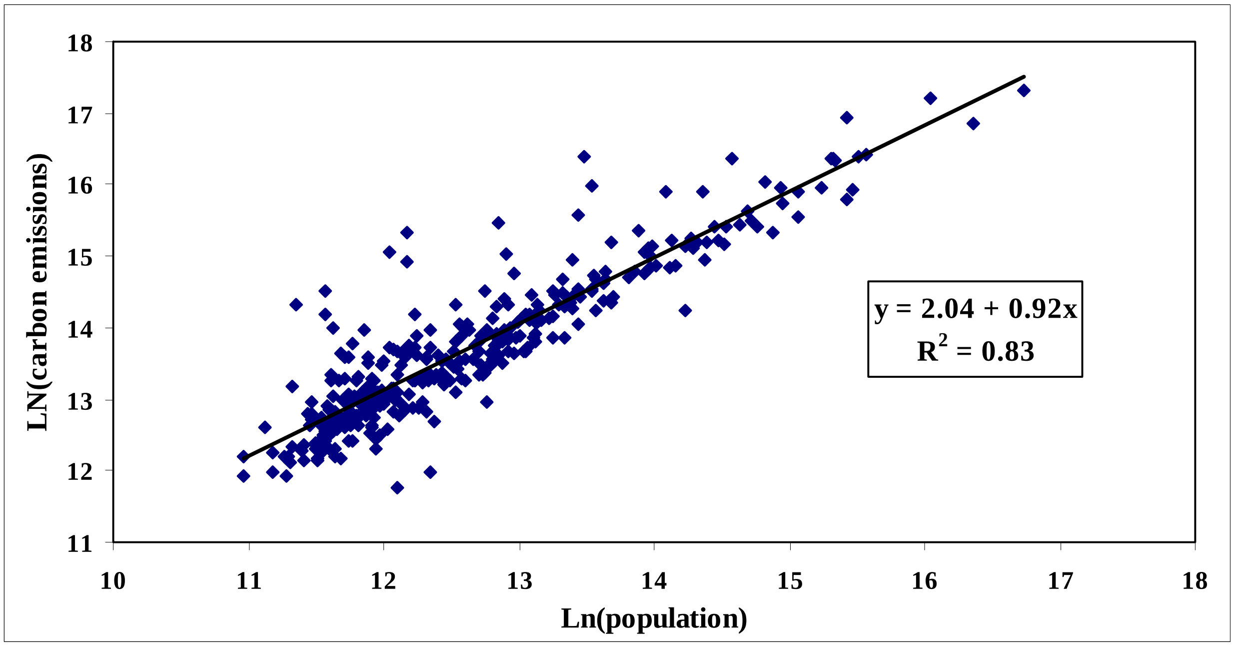
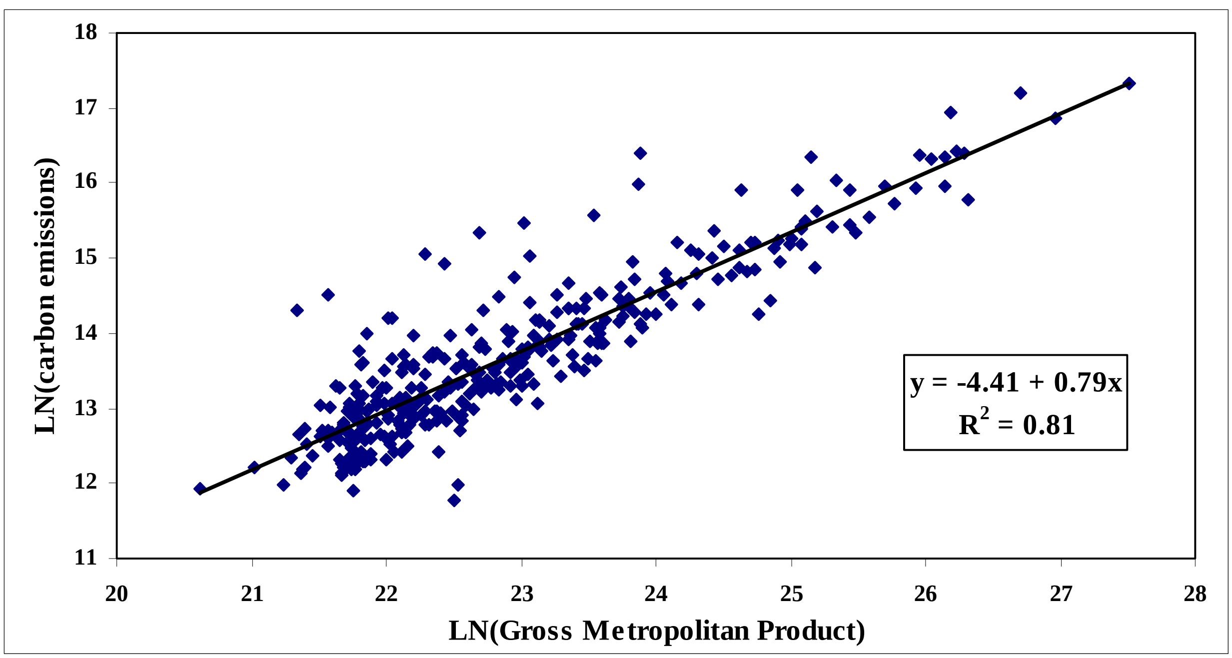


Figure 2. Scaling of metropolitan carbon emissions with economic output.



Author Bio

José Lobo:

School of Human Evolution and Social Change, and W.P. Carey School of Business, Arizona State University, Tempe, Arizona, 85287. E-mail: jose.lobo@asu.edu.

Deborah Strumsky:

Department of Geography and Earth Sciences, University of North Carolina at Charlotte, McEniry 429, 9201 University City Boulevard, Charlotte, NC 28223. E-mail: dstrumsky@uncc.edu.

Luis Bettencourt:

Theoretical Division, Los Alamos National Laboratory, Los Alamos NM 87545 U.S.A. E-mail: lmbett@lanl.gov

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