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Foundations of Urban Science

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Green MSAs, Dirty Cities

There has recently been a great deal of interest in formulating a science of cities that is quantitative and predictive. One locus of this research has been the Santa Fe Institute, where Luis Bettencourt and Geoffrey West call for a “'grand unified theory of sustainability' with cities and urbanization at its core” (Bettencourt 2010). This focus on cities and urbanization is due in large part to the fact that 54% of the world's population currently lives in cities, and this percentage is increasing rapidly to a projected 66% by 2050 (U.N. 2014). This transition is occurring simultaneously with another paradigm shift as nations around the world begin to seek a reduction in their carbon emissions in an attempt to mitigate the effects of global climate change. This momentum is building largely because of the recommendations of respected international bodies such as the U.N. Intergovernmental Panel on Climate Change and the United Nations Environment Program which call for global carbon neutrality sometime before 2070 in an effort to stay below the +2° Celsius limit to global warming agreed upon at the 2010 Cancun Climate Conference (U.N. 2014).

To this end, it is vitally important to quantify global patterns of resource and energy use as well as patterns of greenhouse gas emissions so that effective action can be taken. Since cities are where the people are (and thus where the waste is) it is natural to look to the nascent science of cities for help in identifying universal trends that can be leveraged for the purpose of increasing sustainability. One pattern that has been identified is that many diverse properties of cities scale as power-law functions of city size. Furthermore, these power laws have exponents, β, that tend to fall into three distinct classes (Bettencourt et al. 2007). A β significantly greater than one corresponds to urban attributes that scale super-linearly with population such as crime, patents, and other socio-economic indicators. An exponent of approximately one is present for attributes that scale linearly with population like housing and employment. The last group, with β less than one, is perhaps the most interesting from a sustainability viewpoint. This set of urban attributes tends to scale sub-linearly with population size, and represents the economies of scale found in urban infrastructure. This is promising for sustainability because it implies that individuals can become more efficient on a per capita basis simply by moving to a large city and adopting the lifestyle and habits that entails.

One indicator that is of prime importance for climate change mitigation is the quantity of greenhouse gases (expressed in Co2 equivalents) that are produced in a city. The effect of urban population size on Co2 emissions has been assessed by several groups with quite contradictory results due to drastically different definitions of what makes a city. The first method takes United States Metropolitan Statistical Areas (MSAs) as the unit of study, and shows a slightly sublinear relationship between Co2 emissions and population (Fragkias et al. 2013). The second method uses the City Clustering Algorithm to grow city boundaries in an organic manner that ignores administrative boundaries and yields strong superlinear scaling of emissions (Oliveira et al. 2014). The analysis in this paper follows the MSA method used by Fragkias et al. and achieves comparable results.

Methods

Total carbon emissions were retrieved at the county level from the Vulcan Project for the year 2002 (Vulcan 2002). This was joined with county level data from the U.S. 2000 census. The combined county data was then aggregated into MSAs using a dataset from the Bureau of Economic Analysis (BEA 2013) mapping counties to their statistical areas. Data cleaning was almost negligible, but included renaming of a few key columns and deletion of unnecessary ones. Critically, all MSAs with population less than 100 thousand were excluded from analysis.

Analysis

The key finding in this paper is the existence of a strong linear relationship between the logarithm of total population of an MSA and the logarithm of total carbon emissions (expressed in Co2e). This finding, visible in Figure 1, of linear behavior in a log/log plot points to the existence of a power-law relationship with an exponent, β corresponding to the slope of the linear fit in the log/log plot. For our emissions data, OLS regression yielded a model of $y = 2.656\ (\pm 0.451) + x*0.9143\ (\pm 0.035)$ with $R^2 = 0.668$ indicating a scaling exponent of $\beta = 0.9143$. This exponent is significantly different from one, indicating mild gains in efficiency for large cities. Furthermore, this result is entirely consistent with the findings of Fragkias et al. who found an exponent for carbon emissions of $\beta = 0.933$ when analyzing panel data across 10 years.

Relationships between total emissions and other urban attributes were also investigated but the results were not nearly as conclusive. Figure 2 shows log per capita carbon emissions versus log population. A linear relationship is hardly visible, which is actually a predicted result of the scaling theory. If emissions really do scale sub linearly, then per capita measures of emissions (which assume linear scaling) should not be a meaningful measurement and should not correlate strongly with population. Perhaps a more contentious result is visible in Figure 3 which shows log emissions vs log density. Many advocates of dense urban living argue that living in close quarters reduces energy and fuel consumption because of more compact living spaces and decreased travel distances. However, among these data it was found that emissions are actually positively correlated with density. One way to reconcile this is through the arguments of Oliveira et al. who show that densities are not consistent across MSAs. That is, they show that higher density MSAs also tend to be higher population and therefore yield higher levels of carbon emissions.

Next we consider the sample of MSAs with respect to their *Scale-Adjusted Metropolitan Indicators* (SAMIs), also known as residues *(*Bettencourt et al. 2010). These residues indicate a given city's deviation from its expected value according to the power law. Figure 4 shows the SAMIs ranked according to their value. It can be seen that Farmington, NM is MSA in the list with the largest positive deviation with regards to carbon emissions. This can likely be attributed to the relatively small population combined with the presence of a coal-fired power plant (Robinson-Avila 2014). Figure 5 shows a histogram of the distribution of the residues. This data differs significantly from the examples given by Bettencourt in that the distribution is not symmetric and shows a large positive skew. Therefore the data can not be characterized by a laplace distribution as is argued in the paper.

Discussion

It has been shown, both in this work and previously by Fragkias, that greenhouse gas emissions follow a power-law distribution with respect to city population size, and also that these emissions scale sub-linearly meaning that larger cities are more efficient on a per capita basis. However, this result holds only when a "city" is defined as a metropolitan statistical area and previous work has shown that different definitions yield drastically different results. This indicates that there is still a great deal of work to be done to find definitions that give actionable results. This paper also examined the power-law residues for carbon emissions, thereby identifying outlier MSAs, while also showing that the SAMIs for Co2 do not follow the idealized laplace distribution suggested by Bettencourt, West, et al. to categorize residuals.

Appendix

Figure 1:

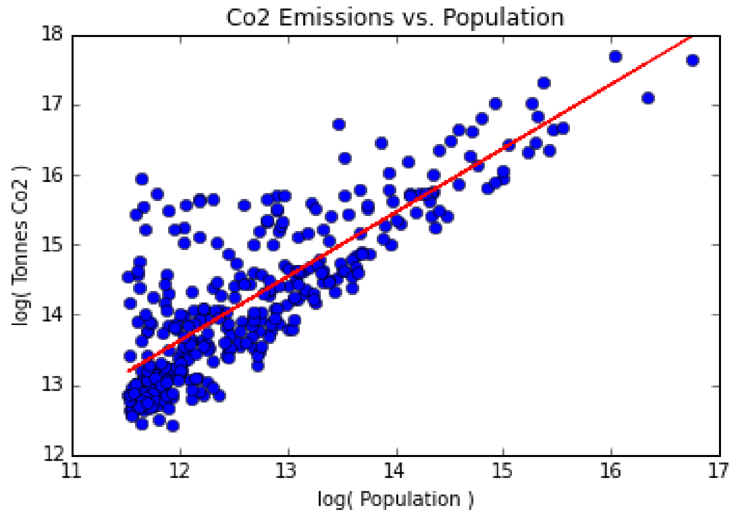


Figure 2:

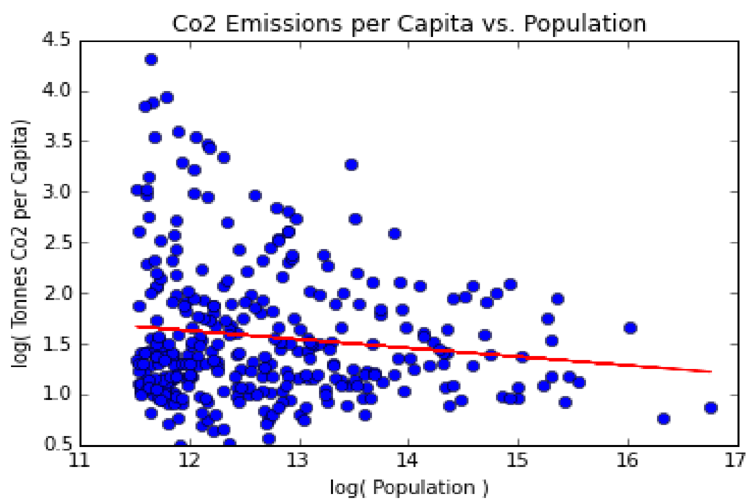


Figure 3:

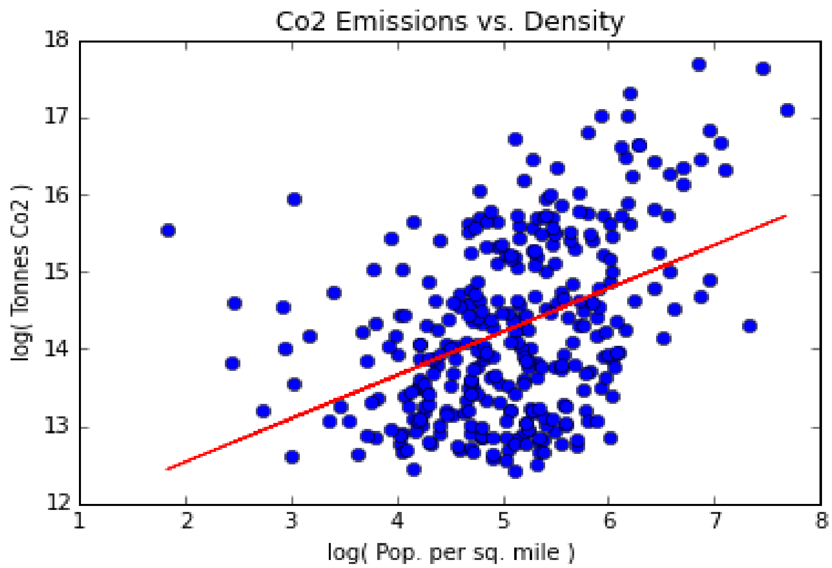

Co2 Emissions vs. Density
log(Tonnes Co2)
log(Pop. per sq. mile)
18
17
16
15
14
13
12
1
2
3
4
5
6
7
8

Figure 4:

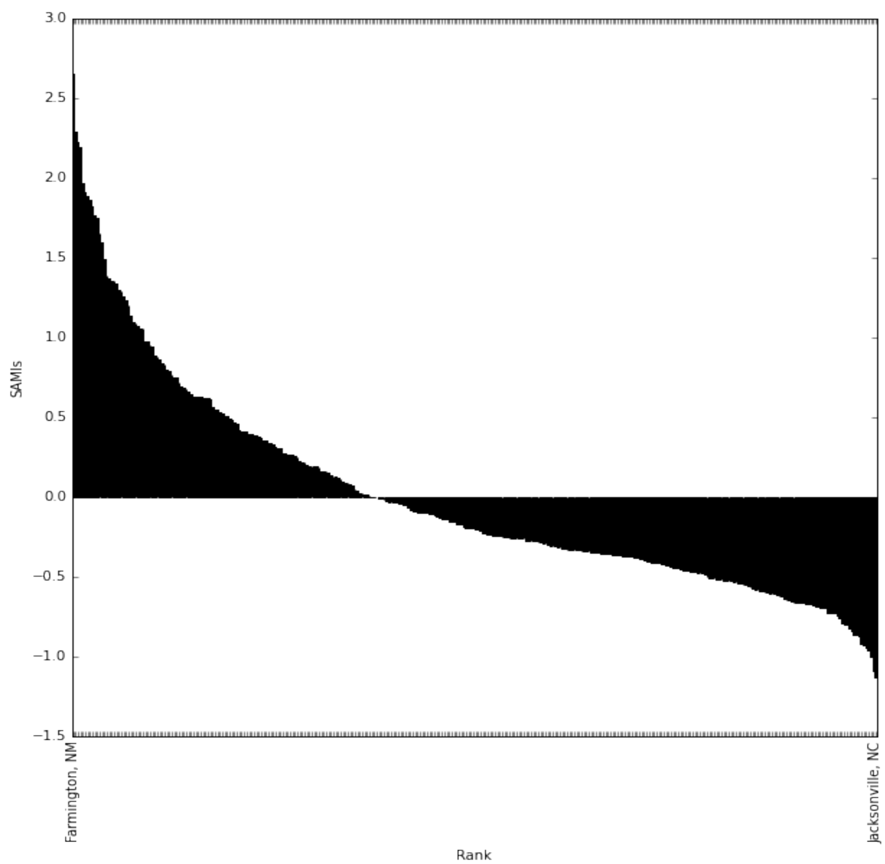
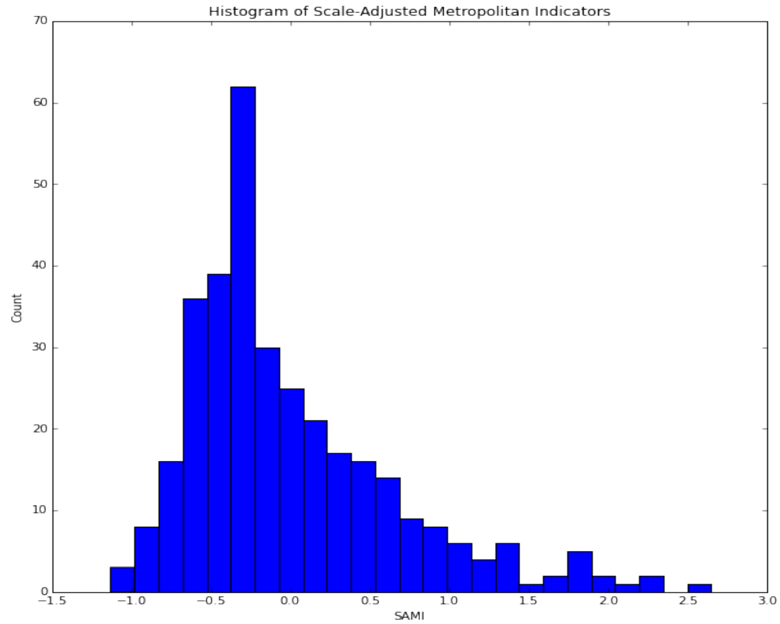

SAMIs
Rank
Farmington, NM
Jacksonville, NC
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5

Figure 5:



Histogram of Scale-Adjusted Metropolitan Indicators
70
60
50
40
30
20
10
0
Count
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
SAMI

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