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Geoffrey West, Luis Bettencourt and others have found what they claim to be a universal law of cities – that as cities grow, aspects of the city constantly grow either superlinearly – as the city grows the aspect grows faster – or sublinearly – as the city grows the aspect grows slower. For example, crime increases superlinearly and infrastructure grows sublinearly[1]. Does this pattern hold for carbon emissions? Do we see any correlation between a city's size or its density and its carbon emissions per capita? And if so does it exhibit either superlinear or sublinear scaling?

Christopher Jones and Daniel Kammen modeled the carbon consumption for a hypothetical demand of goods and services based on various sources such as survey data[2]. When mapped by zip code tabulation area (ZCTA) the model produces results such as Figure 0. An interesting bullseye pattern appears around city centers with low emissions per household in the center, high emissions in the suburbs, and then dropping back down as the area gets more rural.

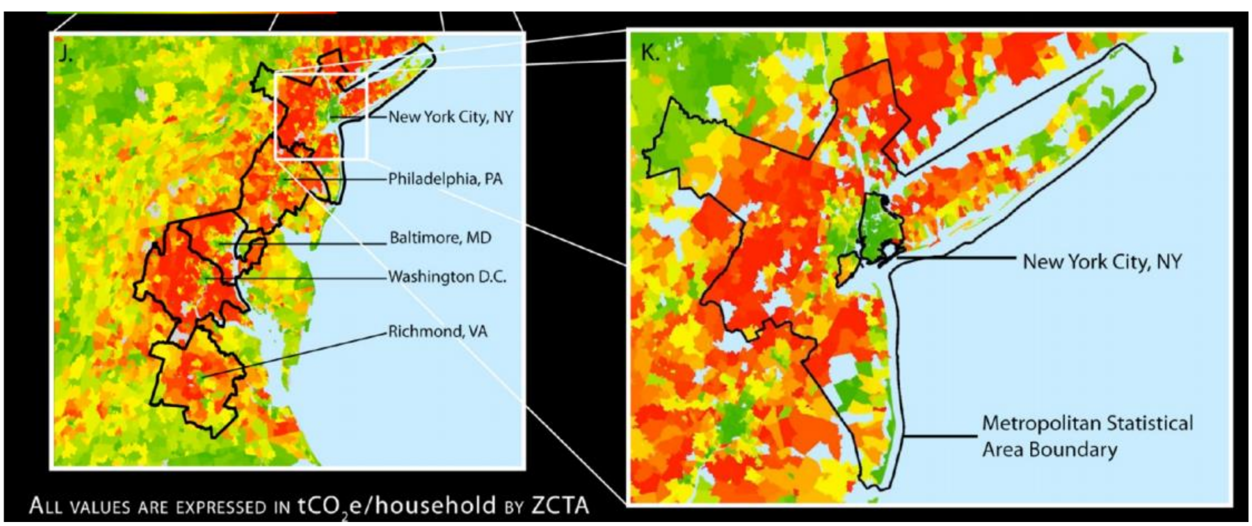

Figure 0: Total carbon emissions per household grouped by zip code tabulation areas. Green is lower emissions and red is higher emissions. A distinct bullseye pattern of can be seen around cities with the city centers having low emissions per household, the suburbs having very high, and then emissions dropping back down as the area gets more rural. (Jones, Kammen)

This could mean that when devising our own classification for cities, it may be a mistake to include the outlying suburbs along with the city centers because a large suburb does not reflect consumption in cities. On the other hand, if a city can't exist without sprawling suburbs around it then a city's suburbs should be included.

Despite this stark difference in consumption, when aggregating the results into a number of areas including cities and counties, they found no overall correlation between population density and CO2 emissions except for the just the 100 largest city centers, where a negative correlation was found.

The Vulcan project attempts to quantify actual CO2 emissions (where it is produced rather than consumed). The Vulcan data does not exhibit this distinctive bullseye that the model does, which could indicate that there in actuality there isn't an increase in emissions from a city center to its surrounding suburbs[3].

Data Sources and Data Cleaning

Four datasets were used – the Vulcan CO_2 emissions data and three datasets from the U.S. Census with county population, county area and a mapping from counties to their MSA (Metropolitan and Micropolitan Statistical Areas) if any. The Vulcan dataset contains county level carbon emissions from 2002 for a number of different sectors, as well as total emissions for the county. The data was originally provided as an Excel spreadsheet. Excel was used to remove comments and convert it to CSV for analysis. The Census came from three different Excel files with a number of fields and comments. The relevant data is the 2002 county population, area and MSA to county mapping. Excel was used to remove extraneous fields and comments and to convert to CSV. The carbon, population and land area datasets contained the county FIPS (Federal Information Processing Standard) code as a five digit code, while the MSA dataset contained them as a two digit state and three digit county code, so these two columns were merged into one. Then the four datasets were merged on the FIPS code. Several counties had zero area in the dataset, so these counties were ignored. For analysis at the MSA level, counties were aggregated by the MSA code. For both individual counties and MSA aggregates, several fields were derived from the given data including CO_2 emissions per capita, CO_2 emissions per square mile, and population density per square mile.

Analysis

There are two primary questions we have. First, how does the total population of a city affect its emissions? Are sprawling megacities more or less efficient than smaller cities? Second, how does the population density affect the emissions? Will a city of a million people emit more or less than another city of a million which is half the area?

First the analysis was done at the most granular level available, the county level and the results are shown in Figure 1. The total CO2 emissions were graphed versus total population of the county and CO2 emissions per capita versus population density of the county. Then ordinary least squares (OLS) linear regression was done to measure any potential correlation. The results that total CO2 emissions grow as population grows and that CO2 emissions per capita decreases as population density increases. This analysis was repeated at the MSA level and the results as shown in Figure 2 are the same.

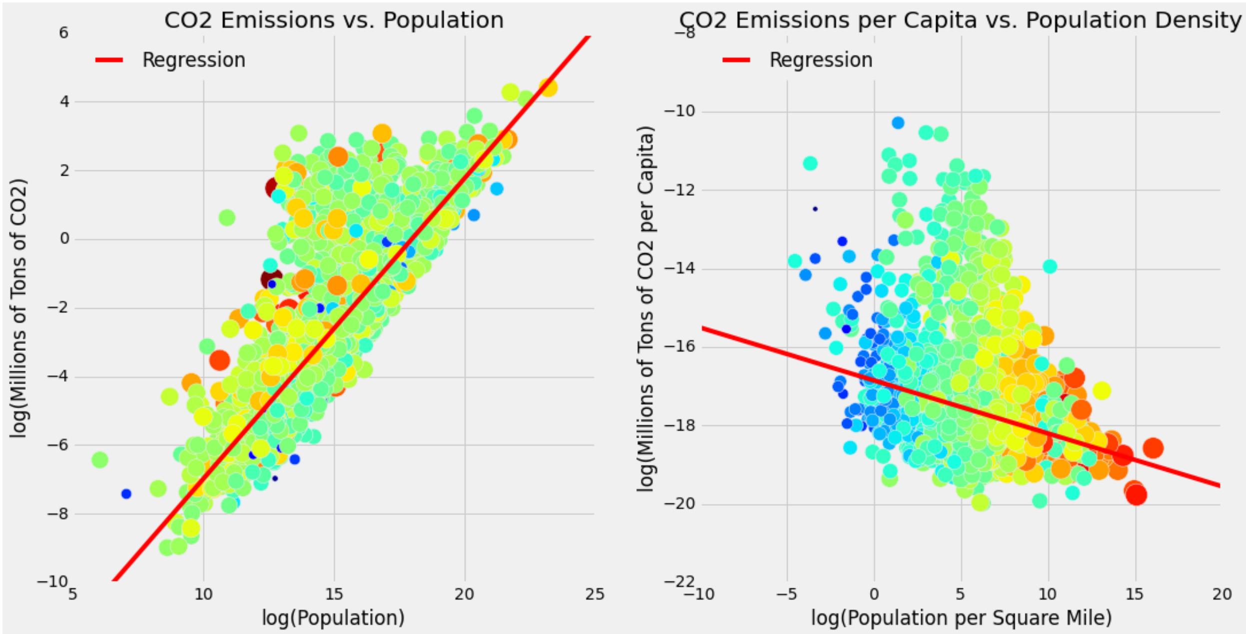

Figure 1: County level log(Total Emissions) vs. log(population) (left) and vs. log(population density) (right). In the left graph point size and color is based on the county's land area with larger/redder points indicating larger area and in the right size and color is based on total population of the county with larger and redder points having a higher population. Red line shows the OLS regression. For the left graph the slope of the line is 0.8755 and for the right it's -0.1351.

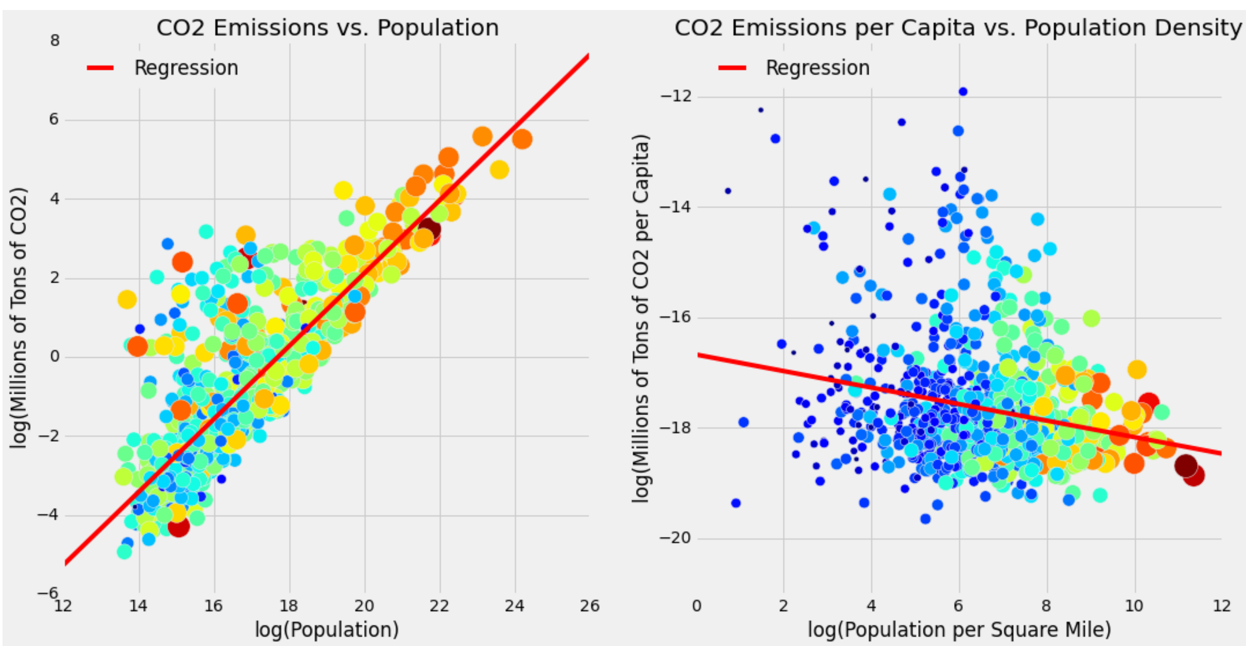

Figure 2: MSA level log(Total Emissions) vs. log(population) (left) and vs. log(population density) (right). In the left graph point size and color is based on the county's land area with larger/redder points indicating larger area and in the right size and color is based on total population of the county with larger and redder points having a higher population. Red line shows the OLS regression. For the left graph the slope of the line is 0.9238 and for the right it's -0.1496.

More interestingly is that both total emissions versus population and emissions per capita versus population density are sublinear relationships. This means that as the population grows total emissions will flatten out and as population density grows emissions per capita will flatten out. Figure 3 shows this effect.

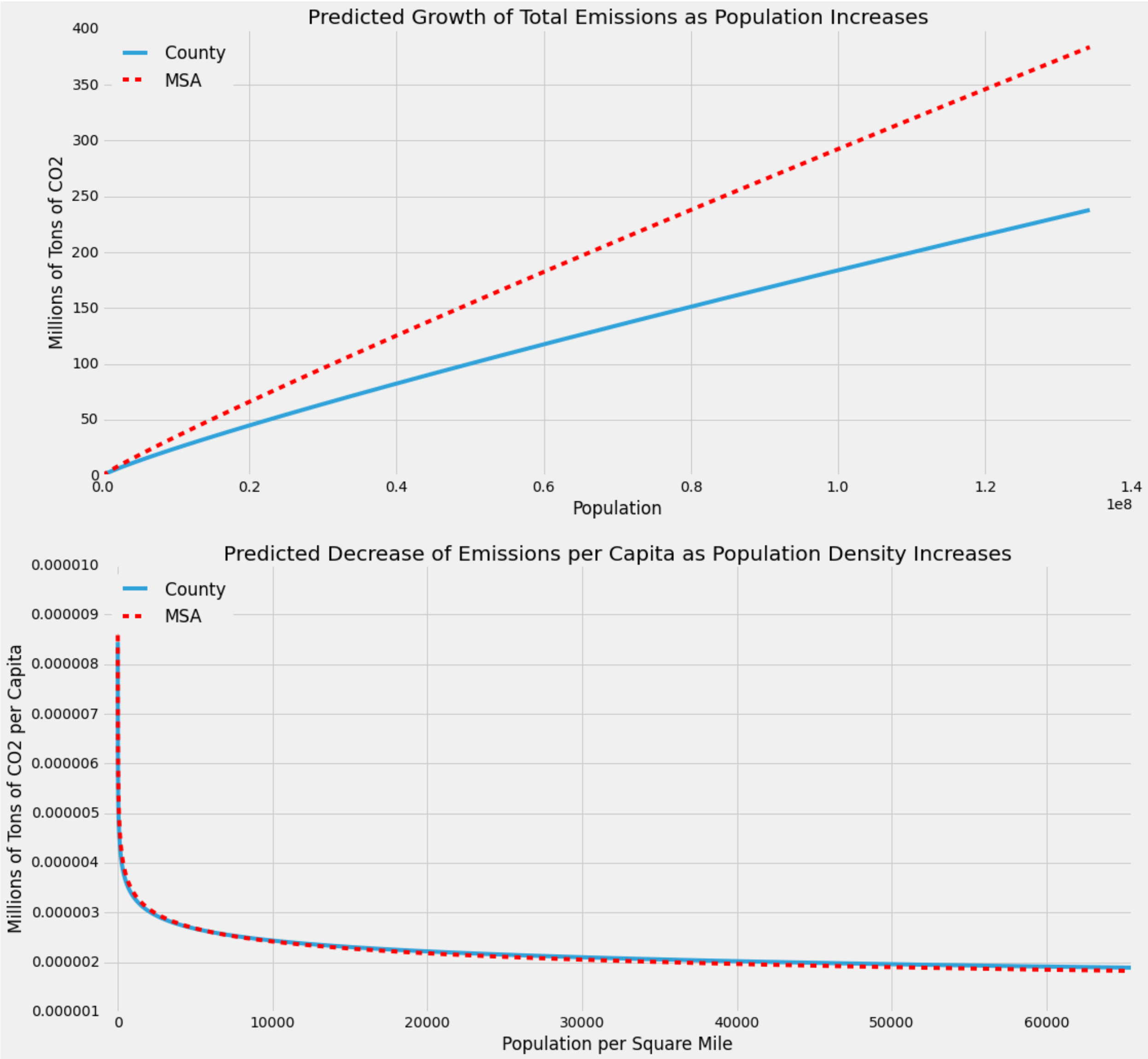

Figure 3: Results from County level and MSA level regressions plotted on a linear scale. As population increases total emissions grow slightly more less than linearly. As population density grows emissions per capita falls off rapidly until flattening out around 10000-20000 people per square mile.

As shown, the returns on increasing density very quickly disappear and past 20 to 30 thousand people per square mile there is very little gain for increasing density. For example, this model predicts that to cut emissions per capita in Manhattan in half, the population per square mile would need to be increased from about 60,000 people today to about 4,000,000 people per square mile, which would equal over 100,000,000 people in Manhattan. On the other hand, because the emissions appear to go up sublinearly as the city's total population increases, a city could still grow wide even if there are only negligible gains to growing denser.

To test this hypothesis that there may be an optimal city density but not city area, we can look at the correlation between city land size and CO_2 emissions per capita. Since we're interested in cities that are fairly dense to see if there is any effect on them growing wide, we'll constrain the regression to counties and MSAs with population density among the top 25th percentile of population density. Figure 4 shows the results.

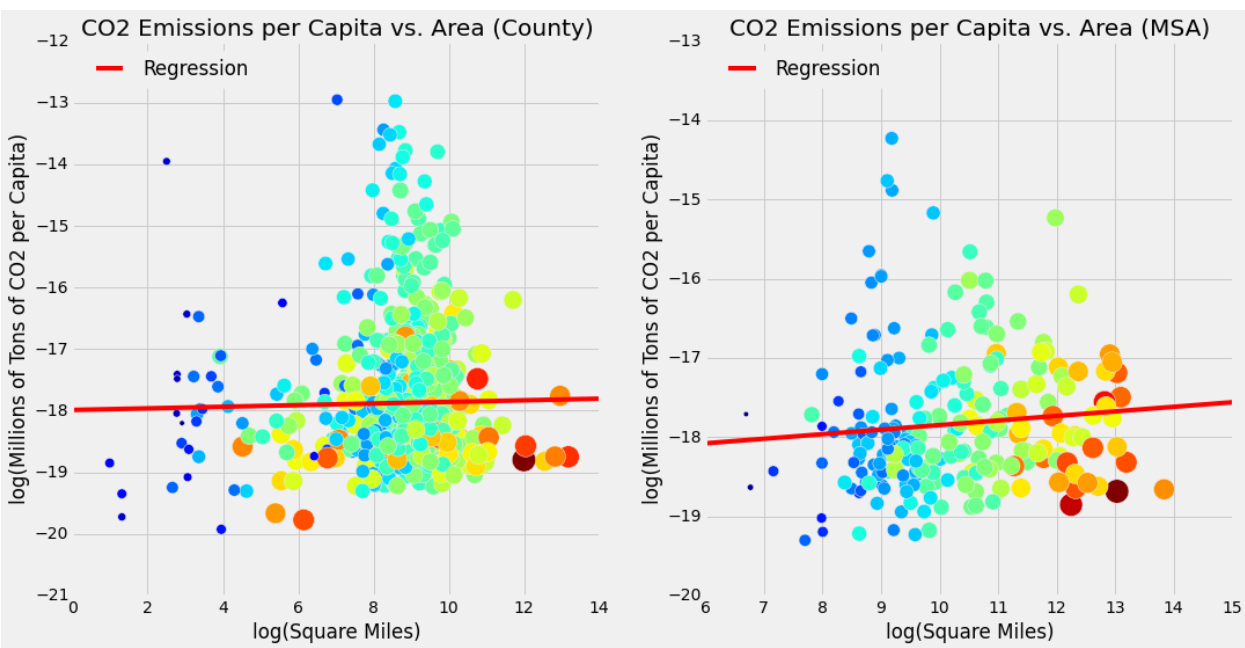

Figure 4: County level (left) and MSA level (right) log (Emissions per capita) vs. log(square miles). Points are colored and sized based on population. Red line shows the OLS regression. Both regression results include 0 in the 95% confidence interval.

At a 5% confidence level there is no correlation between the area and the CO_2 emissions per capita. This would indicate that a dense city could continue to expand in area and a city's population could continue to increase even once it no longer is fruitful to build the city more densely.

Conclusion

Using the 2002 Vulcan CO_2 emissions data a positive sublinear correlation was found between total population and total emissions as well as a negative sublinear correlation between population density and emissions per capita, aggregated at both a county and MSA level. The model predicts that the gains in building densely fall off quickly and there are only marginal gains for getting more dense than 20,000 to 30,000 people per square mile. On the other hand, no correlation was found between a city's area and emissions when considering already "dense" areas, therefore indicating a city may continue to grow wider, thus in total population, without limit.

Appendix 1: Top 10 and Bottom 10 MSAs by CO2 emissions per capita:

Top MSAs	**Population**	**CO2 Emissions**	**CO2 Per Capita**	**Population Density**
Los Angeles-Long Beach-Anaheim, CA	12634977	26.645275	0.000002	2605.004876
Fresno, CA	828245	1.785504	0.000002	138.903657
McAllen-Edinburg-Mission, TX	607449	1.438398	0.000002	386.971811
New York-Newark-Jersey City, NY-NJ-PA	19232075	45.614558	0.000002	2304.953978
Phoenix-Mesa-Scottsdale, AZ	3496957	8.441516	0.000002	239.965813
El Paso, TX	692083	1.671084	0.000002	123.937924
Raleigh, NC	863488	2.100678	0.000002	408.116117
San Jose-Sunnyvale-Santa Clara, CA	1728245	4.220193	0.000002	644.927698
Miami-Fort Lauderdale-West Palm Beach, FL	5212602	12.734297	0.000002	1016.979965
Portland-Vancouver-Hillsboro, OR-WA	2010666	4.98212	0.000002	300.813723
Bottom MSAs	**Population**	**CO2 Emissions**	**CO2 Per Capita**	**Population Density**
Cleveland-Elyria, OH	2140552	16.962121	0.000008	1067.921234
New Orleans-Metairie, LA	1332487	10.672714	0.000008	391.965583
Louisville/Jefferson County, KY-IN	1137272	9.191798	0.000008	316.375543
Tulsa, OK	874815	7.09101	0.000008	139.281791
Knoxville, TN	765948	6.686412	0.000009	218.817903
Winston-Salem, NC	585775	5.511368	0.000009	290.805334
Charleston-North Charleston, SC	566543	5.946698	0.00001	218.661423
Birmingham-Hoover, AL	1065089	14.164308	0.000013	201.034534
Allentown-Bethlehem-Easton, PA-NJ	756321	11.376941	0.000015	518.251711
Baton Rouge, LA	713558	18.546887	0.000026	177.065053

Appendix 2: Top 10 and Bottom 10 Counties by CO2 emissions per capita:

Top Counties	**Population**	**CO2 Emissions**	**CO2 Per Capita**	**Population Density**
Chattahoochee, GA	19189	0.01848	9.63E-07	77.135507
Coryell, TX	73341	0.071437	9.74E-07	69.731688
Poquoson, VA	11625	0.011658	1.00E-06	749.033505
Kings, NY	2477380	2.762536	1.12E-06	35085.39867
Lexington, VA	6877	0.007931	1.15E-06	2761.84739
Bronx, NY	1348285	1.620503	1.20E-06	32079.11016
Maverick, TX	48315	0.058876	1.22E-06	37.743735
Estill, KY	15234	0.019129	1.26E-06	59.992911
Starr, TX	55862	0.081179	1.45E-06	45.675459
Asotin, WA	20511	0.029986	1.46E-06	32.283502
Bottom Counties	**Population**	**CO2 Emissions**	**CO2 Per Capita**	**Population Density**
Millard, UT	12222	3.815449	3.12E-04	1.854873
Pleasants, WV	7566	2.368028	3.13E-04	57.87501
Stewart, TN	12679	4.748255	3.74E-04	27.654423
Emery, UT	10553	4.029143	3.82E-04	2.370475
North Slope, AK	7149	2.792107	3.91E-04	0.080491
Platte, WY	8694	3.567538	4.10E-04	4.169924
Rosebud, MT	9203	4.179491	4.54E-04	1.836058
Wilcox, AL	12928	8.485902	6.56E-04	14.547419
Mercer, ND	8424	5.67497	6.74E-04	8.057466
Oliver, ND	1921	1.538196	8.01E-04	2.655075

[1] Bettencourt, L., & West, G. (2010). A unified theory of urban living. *Nature,* 912-913.

[2] Jones, C., & Kammen, D. (2014). Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density. *Environmental Science & Technology Environ. Sci. Technol.,* 895-902.

[3] Gurney, K., Mendoza, D., Zhou, Y., Fischer, M., Miller, C., Geethakumar, S., & Stephane De La Rue Du Can. (2009). High Resolution Fossil Fuel Combustion CO 2 Emission Fluxes for the United States. *Environmental Science & Technology Environ. Sci. Technol.,* 5535-5541.