Validating CDIAC's Population-Based Approach to the Disaggregation of Within-Country CO₂ Emissions

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ABSTRACT

The Carbon Dioxide Information Analysis Center produces and distributes a data base of CO₂ emissions from fossil-fuel combustion and cement production, expressed as global, regional, and national estimates. CDIAC also produces a companion data base, expressed on a one-degree latitude-longitude grid. To do this gridding, emissions within each country are spatially disaggregated according to the distribution of population within that country. Previously, the lack of within-country emissions data prevented a validation of this approach. But emissions inventories are now becoming available for most U.S. states. An analysis of these inventories confirms that population distribution explains most, but not all, of the variance in the distribution of CO₂ emissions within the United States. Additional sources of variance (coal production, non-carbon energy sources, and interstate electricity transfers) are explored, with the hope that the spatial disaggregation of emissions can be improved.

INTRODUCTION

The Carbon Dioxide Information Analysis Center produces and distributes a data base of CO₂ emissions from fossil-fuel combustion and cement production, expressed as global, regional, and national estimates. This data base was originally developed primarily to support studies of the global carbon cycle, as it was appreciated that fossil-fuel combustion and cement production accounted for a significant...
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fraction of anthropogenic emissions of carbon dioxide to the atmosphere (the other major source being changes in land use and land cover). Initially, global, regional, and national resolution was sufficient. As global modeling of the carbon cycle became more sophisticated, analyses (facilitated by the increasing availability of isotopic data) of transport between the northern and southern hemispheres promised to improve the quantification of sources and sinks and, especially, to shed light on the issue of the so-called "missing sink," the discrepancy between known sources and sinks and the observed increasing atmospheric concentration of CO₂. Country-level emissions estimates no longer provided the latitudinal resolution needed for interhemispheric transport studies, especially in the case of areally large countries, such as Russia, China, and the United States.

CDIAC responded to this need for improved spatial resolution by producing (with outside collaborators) and distributing a companion data base, expressed on a one-degree latitude-longitude grid. This data base demonstrated, on a decadal time scale, a southward movement of the latitude of maximum emissions. Another related data base available from CDIAC provides spatial detail on the changing isotopic signature of CO₂ from fossil-fuel combustion and cement manufacture.

To do this gridding, emissions within each country are spatially disaggregated according to the distribution of population. This approach, obviously, is based on the assumption that emissions occur where people are located. Population seemed to be the best available proxy with which to distribute within-country emissions. Various population data bases have been used. They offer estimates for different years, and they vary somewhat among themselves, especially in terms of how the population of large metropolitan areas is distributed among gridcells, and how gridcells (and populous cities) near national borders are assigned to countries.

Previously, the lack of consistent within-country emissions data prevented a test of how well the population proxy succeeds in describing the within-country distribution of emissions. And there was reason to suspect the assumption that the distribution of emissions would necessarily reflect the distribution of population. The assumption seemed more reasonable for certain kinds of emissions (e.g., combustion of petroleum-based automotive fuels) than for others (e.g., combustion of coal at remote mine-mouth power plants).

But emissions inventories are now becoming available for many U.S. states. Through the cooperative State and Local Climate Change Program of the U.S. Environmental Protection Agency, nearly 30 states (and Puerto Rico) have compiled inventories of greenhouse-gas emissions for 1990 (and, in some cases, other years), with another six states having inventories under way (Figure 1). Fortunately, the states are more-or-less consistent in following a single methodology, although they differ in some respects, as described below.

METHODS AND RESULTS

Emissions estimates from the state reports (Table 1) were compiled. In most cases, emissions estimates by fuel type had to be extracted from the reports and re-totaled; the reports generally totaled emissions by end-use sector (commercial, residential, industrial, transportation, utility) rather than by fuel type. In some cases, it was necessary to correct errors in the reports (after discussion with the authors of, or contacts for, the specific state reports, to confirm the nature of the errors). In other cases, emissions attributable to out-of-state generation of imported electricity had to be "backed out," to avoid double-counting emissions (only Iowa and New Jersey included emissions attributable to imported electricity). In two cases (Tennessee and Washington), emissions attributable to biomass fuels were excluded for consistency with CDIAC's approach, in which emissions from biomass are not considered net emissions, as the biomass fuel cycle is theoretically a closed loop for carbon (other than fossil-fuel imports, such as fuels for harvesting equipment), with plants removing carbon from the atmosphere during photosynthesis.

Population data for 1990 were obtained from the U.S. Bureau of the Census [http://www.census.gov/population/estimates/state/ST9096T1.txt, P25-1127 (National and State Population Estimates: 1990-1994), and
The correlation between state population and state CO₂ emissions for 1990 was plotted (Figure 2). If state population perfectly explained CO₂ emissions, then the points would all be expected to fall exactly on a straight line. The non-parametric Spearman's Rank Correlation test (based on a comparison of the rank-ordered lists of states by emissions and by population) indicated a highly significant correlation (P<0.0002 for n=28).

Nevertheless, the points did not all lie perfectly along a straight line through the origin. That is, other factors besides population were responsible for the distribution of emissions within the United States. The challenge is to identify data sets that are readily and uniformly available and that will improve the predictability of CO₂ emissions at the state level over that achieved using population alone. We speculated that the distribution of coal production might account for some of the remaining spatial variability, for two reasons: coal results in a greater emission of CO₂ per energy yield than do petroleum fuels and natural gas, and coal is relatively expensive to transport and often combusted in mine-mouth power plants. Thus, we felt that emissions might tend to mirror the location of coal production. Coal production data for 1991 (1990 data were not available for this analysis) were obtained from the Energy Information Administration (EIA) of the U.S. Department of Energy (ftp://ftp.eia.doe.gov/pub/coal/cia_95_tables/t1p01.txt). When the states with significant 1991 coal production (at least 5 short tons per capita; 1 short ton or 2000 pounds equals 0.907 metric tons) are identified, they are seen to fall disproportionately above the mean trend line (Figure 2). Thus, coal production does appear to explain some of the distribution of CO₂ emissions not attributable to population.

We also hypothesized that per-capita CO₂ emissions would be strongly influenced by imports of electricity (i.e., electricity used within a state but generated in another state, which would be listed as the source of the CO₂ emissions) and by non-fossil sources of energy (e.g., nuclear, hydroelectric, photovoltaic, biomass, wind, geothermal). A relationship is suggested between per-capita CO₂ emissions and per-capita electricity imports (Figure 3) and per-capita non-fossil energy consumption (Figure 4).

We performed a detailed statistical analysis, using the SAS (SAS Institute, Cary, North Carolina) linear regression procedure on untransformed and log-transformed data, to further quantify the fraction of variability in CO₂ emissions attributable to population, coal production, electricity imports, and non-fossil energy sources. In the untransformed model, the dependent and explanatory variables were used in the linear regression model without being transformed. In the transformed model, the dependent and explanatory variables (except for electricity imports) were used in the linear regression model after being transformed. For coal production and non-fossil energy sources, the transformed value was the log of 1 + the untransformed value; and for CO₂ emissions and population, the transformed value was the log of the untransformed value.

Our analysis indicated that population explained 85% and 84% (in the untransformed and transformed models, respectively) of the variance in CO₂ emissions, and that the effect of population on CO₂ emissions was significant at the P<0.0001 level. The significance of the other variables depended on whether the data were transformed or not. In the untransformed model, electricity imports were significant at the P<0.006 level and coal production at the P<0.06 level (together explaining an additional 7% of the variance); non-fossil energy was not significant (P>0.16), and explained less than an additional 1% of the variance. In the transformed model, only coal production joined population as a significant factor (P<0.0001), explaining an additional 9% of the variance; electricity imports and non-fossil energy were not significant (P>0.86 and P>0.23, respectively), together explaining less than an additional 0.5% of the variance. Thus, population is the single most important factor determining CO₂ emissions, coal production explains a significant amount of the remaining variance, and the significance of the effect of electricity imports depends on the particular statistical model employed. Non-fossil energy, while suggestive as a factor, was not found to be a statistically significant determinant of CO₂ emissions.
CONCLUSIONS

These inventories confirm that population distribution explains most, but not all, of the variance in the state-level distribution of CO₂ emissions within the United States. Coal production appears to be an important secondary factor, consistent with our expectations. Additional sources of variance include imports of electricity from other states (which report the emissions in their own inventories), and perhaps - though not statistically demonstrable - energy from sources that are in-state but do not emit greenhouse gases.

While there is no guarantee that the sources of variance in the United States are applicable to other countries, this analysis does provide a measure of confidence in CDIAC's approach to disaggregating within-country CO₂ emissions based on population distribution. To the extent that (1) we can identify sources of variance (and quantify their contribution), (2) this information is available, and (3) the contribution of the sources to the distribution of emissions within the United States is applicable elsewhere, we can improve the spatial disaggregation of emissions.

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<table>
<thead>
<tr>
<th>State</th>
<th>Report Title</th>
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<td>California</td>
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Wisconsin

Figure 1. Distribution and status of state greenhouse-gas emissions inventory reports.
Figure 2. Correlation of state fossil-fuel CO₂ emissions and population. States with 1991 per-capita coal production of ≥5 short tons are labeled. One short ton or 2000 pounds equals 0.907 metric tons.
Figure 3. Correlation of state fossil-fuel $\text{CO}_2$ emissions and non-carbon energy consumption. One short ton or 2000 pounds equals 0.907 metric tons. One Btu = $1.06 \times 10^3$ joules.
Figure 4. Correlation of state fossil-fuel CO$_2$ emissions and electricity imports and exports. Imports are shown as positive values on the horizontal axis, exports as negative values. One short ton or 2000 pounds equals 0.907 metric tons. One Btu = $1.06 \times 10^3$ joules.
1990 Fossil-Fuel CO2 Emissions
(1000 short tons CO2)
Per-Capita CO2 Emissions (1000 short tons CO2) vs. Per-Capita Electricity Imports (10^6 Btu/capita) (+) and Exports (-)

The graph shows a negative correlation between per-capita CO2 emissions and electricity imports/exports. As the per-capita CO2 emissions decrease, the imports/exports tend to increase.
Keywords: carbon dioxide, emissions, fossil fuels, population, electricity, renewable energy