URBANIZATION & LOCAL DRIVERS OF EMISSIONS IN THE UNITED STATES: A NATIONWIDE STUDY OF DECLINING EFFICIENCIES OF SCALE*

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ABSTRACT

A paradox exists in the literature on environmental impacts of urbanization: Cities are said to be environmentally efficient and to generate negative environmental change, particularly when it comes to carbon emissions. Improving knowledge of this apparent contradiction requires social scientists to complement existing case studies and cross-national research by examining multiple dimensions of urbanization and how they contribute to environmental outcomes at and from the local level. We advance an analytical framework for conducting such research, which we then test with a nationwide study of local drivers of carbon emissions in the United States. Results reveal how different dimensions of urbanization – population concentration, land-use intensity, and systemic position – push against one another to decrease carbon efficiencies at higher levels of urbanization in ways that exert far greater influence than commonly presumed factors such as household density, alternative transit, and political commitment to global mitigation campaigns. Implications are discussed.

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David Harvey (1996: 429) has argued that "integration of the urbanization question into the environmental-ecological question is *sin qua non* for the twenty-first century." We contend that nowhere is this integration more pressing than in understanding connections between rising levels of urbanization and anthropogenic carbon dioxide emissions, which scientific consensus holds to be the primary contributor to global climate change (IPCC 2007). Yet, current research on links between urbanization and carbon emissions presents us with a paradox.

On the one hand, sociological studies on the subject have focused almost exclusively on national-level processes suspected of having negative consequences for the global environment (Fisher and Freudenburg 2004; Jorgensen and Clark 2011; Schofer and Hironaka 2005; York 2008; York et al. 2003a and 2003b). Broadly, this literature conceptualizes urbanization as a component of modernization that brings with it heightened consumption of material resources from other places, which in turn creates rifts in natural metabolic cycles of the planet, including the carbon cycle (Foster 1999; Gibbs and Martin 1958; Grimm et al. 2008; Clark and York 2005). By contrast, growing numbers of population ecologists, planners and economists highlight the positive consequences of urbanization for the environment. Broadly, this literature conceptualizes urbanization as a form of local demographic concentration that brings with it not only cultural innovation and market power but also material efficiencies of scale and density – efficiencies believed to reduce resource use and carbon emissions per capita and per unit of production (Bettencourt and West 2010; Glaeser 2011; Gonzalez 2009; Newman and Kenworthy 1999). Together, these two literatures imply that cities are both environmentally efficient *and* generate negative environmental change.

We contend that this paradox is not just a matter of scale, whereby materially efficient cities drive materially inefficient societies, but also reflects the locally paradoxical nature of urbanization itself. Understanding this paradox requires us to move sociological research "down" in scale to disentangle how urbanization can exert seemingly contradictory pressures on carbon emissions at and from the local level. To pursue this line of research, we assemble a wide-range of social and environmental data for all counties in the continental United States to conduct the most thorough sociological investigation of local urbanization and carbon emissions to date. This investigation integrates insights from urban and environmental sociology to demonstrate the multidimensionality of urbanization and how its effects on carbon emissions are neither good nor bad, but dynamically and dialectically both. Findings affirm this complex relationship and indicate that structural dimensions of urbanization commonly ignored in prior research – e.g., the size of the built environment, relative intensity of land use, and position within a larger urban system – exert much stronger influences on local carbon emissions than commonly highlighted factors such as housing density, alternative transit use, and carbon mitigation campaigns. Below, we lay the foundations for this new line of sociological research, advancing specific hypotheses for empirical investigation.

URBANIZATION, ENVIRONMENT & CARBON EMISSIONS

To date, most sociological research on the global environment has focused on national rather than local dynamics of urbanization. For example, in an otherwise exemplary study, York et al. (2003b) conduct a cross-national investigation of the effects of urbanization, among other variables, on a nation's ecological footprint, defined as the total area of productive land and water needed to sustain current consumption levels. In this study the authors, like other researchers, operationalize urbanization as the percentage of a nation's population living within urban-designated places and then examine the correlation of this variable with the size of the nation's ecological footprint. The aim is to determine whether the relationship between these two variables is negative, which would support the idea that urbanization produces new environmental efficiencies, as ecological modernization theory asserts (Mol and Sonnenfeld, 2000); or whether the relationship is positive, which would support the opposite conclusion, namely that urbanization poses ongoing environmental risks for global sustainability, as metabolic rift theory asserts. Empirical results support the latter by showing that, at the national level, ecological footprints tend to increase with urbanization levels. The authors conclude that is finding is "fully consistent with the work of Foster (1999), who drawing on Marx ([1867], 1967), argues that modernization, because of the separation it generates between country and city, creates a metabolic rift between ecological processes and economic processes" (York et al. 2003b: 294). This conclusion is also consistent with environmental sociology's treadmill of production theory, which although not focused explicitly on urbanization, argues that the constant drive to expand capital – including the fixed capital of cities – increases the volume of resources and energy used to sustain economic production on larger, more intensive scales (Gould, Pellow, Schnaiberg 2008; see also Clement 2010).

Subsequent cross-national research by sociologists on greenhouse gas emissions offers similar findings and conclusions: namely, that more urbanized societies tend to emit greater amounts of harmful gases, all else equal and regardless of whether this outcome is measured in terms of total emissions, per capita emissions, or emissions per unit of gross domestic product (Clark and York 2005; Jorgenson 2006 and 2009; Jorgenson and Clark forthcoming; Lankao, Nychka and Tribbia 2008; York 2008). Indeed, recent analysis of national-level data from 1960 to 2005 confirms that urbanization has remained a strong, consistent and positive predictor of all three measures of emissions over the last half century (Jorgenson and Clark forthcoming). However, as this sociological consensus has mounted, scholars from other fields have begun to take a closer look at links between urbanization and emissions at the local level, offering a different perspective.

For example, population ecologists (Rees and Wackernagel 1996), economists (Glaeser 2011), planners (Florida 2010), and even physicists (Bettencourt et al. 2010) have begun to argue that while urbanization may disrupt global ecosystems, at the local level it also concentrates people and activities in ways that offer material efficiencies critical for global sustainability. Related research explains that these advantages include lower environmental costs per capita for material infrastructure, such as water supply, sewerage, transit, and electric lines (e.g., Glaeser 2011); economies of scale that reduce per capita energy consumption and facilitate alternative transportation options beyond personal motor vehicles; and enhanced social and political capacities for environmental awareness and mitigation practices such as recycling, composting, and other waste reduction activities (see Mitlin and Satterthwaite 1994). In addition, this literature sometimes argues that urban consumption is less materially intensive than suburban and rural consumption because there is less space in which to accumulate the stuff of life, and that bigger cities provide more opportunities to consume high-culture (e.g., museums) that require fewer material resources to accommodate (Owen 2009). The practical implication of these claims, Glaeser (2009) asserts, is that, "If you want to take good care of the environment, stay away from it and live in cities."

This contrast in scale and emphasis from existing sociological research hints at the socio-ecological complexities of urbanization but also obscures them by providing inadequate investigation of links between urbanization and carbon emissions at the local level. Existing sociological research contributes to this shortcoming by focusing almost exclusively on national-level processes of urbanization that remain conceptually and empirically under-specified. Existing studies in other fields do this by focusing narrowly on population concentration at the local level without regard to related processes of land development, intensity of use, and relative position within broader settlement systems. Consequently, understanding of urbanization and carbon emissions at the local level remains incomplete and potentially misleading. To fill this gap, we draw insights from urban and environmental sociology to build an analytical framework that moves sociological research "down" to the local level to emphasize not just population concentration (and its mediating mechanisms), but also the physical transformation of local lands needed to accommodate such concentration and heightened metabolic flows that result. We outline this new analytical framework and associated hypotheses below.

ANALYTICAL FRAMEWORK

The framework we advance here focuses on carbon emitted at the local level by human activities, regardless of whether these activities are intended for local or distant purposes (e.g., to heat a home or to produce goods for other places). Within this framework, we argue that urbanization is not one monolithic process but rather a set of related subprocesses that exert opposite effects on local carbon emissions despite being positively correlated with one another. These sub-dimensions of urbanization include population concentration, which is widely presumed to reduce per capita emissions, along with related but often-ignored dimensions of land-use intensity and systemic position, which we hypothesize operate in the opposite direction. We discuss each of these below, building conceptual bridges between urban sociology and environmental sociology along the way.

Population Concentration

A long line of research in urban sociology has established that population size and density alter the local dynamics of social life (Park 1916; Wirth 1938). Recently, planners, ecologists, and allied researchers have made similar claims with respect to resource use and greenhouse gas emissions, asserting that places with higher population concentrations use less energy and emit less waste per person and per unit of production than other places, all else equal (Brown et al. 2008; Dodman 2009; Ensha 2009; Walker and Salt 2006). Embedded within this assertion are two claims that have become commonly assumed but inadequately demonstrated: (1) that local per capita (and per-unit) emissions actually decline with local population concentration; and (2) that there are certain site-specific factors that mediate, or explain, these reductions.

One reason that these claims have remained under-investigated is that relevant research typically has not measured population concentration per se, but rather the percentage of residents living in urban-designated places, regardless of their size and density. This approach means that residents of New York City and Peoria, Illinois are treated as living in equally “urban” places despite having very different levels of population concentration. Correcting this shortcoming requires moving beyond useful but limited urban-place designations to measure population concentration directly at the local level. Classic urban ecology asserts that this measurement is best done as a product of local population size and density because both factors conjoin to influence the social life of places in tandem (Fischer 1995). This brings us back to the relative lack of research on key mediating factors.

To date, most studies at the local level have either ignored factors presumed to explain population concentration's reduction of per capita and per-unit emissions, or they have focused disproportionately on emissions generated by automobile fuel consumption alone. For example, Newman and Kenworthy (1999) have long argued that population density is inversely related to per capita transport fuel use and emissions. Karathodorou et al. (2010) have clarified that this factor reduces per capita fuel use, and thus emissions, indirectly through reduced car stocks and shorter traveling distances rather than through reduced fuel consumption per distance traveled. These studies point to the importance of mediating factors for explaining the relationship between local population concentration and emissions, but they also beg for further research because they fail to account for the full range of factors presumed to be at work. Most prominently, these factors include increased household density, alternative transit use, and political commitment to local carbon mitigation campaigns, all which are presumed to increase with local population concentration (Zahran et al. 2008). We address this shortcoming by incorporating these three mediating factors directly into our analytical framework for empirical investigation, while also opening the door to other, related dimensions of urbanization that may exert significant counter effects. We turn to these factors next.

Local Land Use Intensity

A striking feature of existing empirical research on urbanization and carbon emissions at any level – local or national – is its relative inattention to the built environment and associated processes of "landscape transformation" (Rudel 2009). Yet without such transformation, population concentration and urbanization more generally cannot occur. Our framework recovers this key process of urbanization and links it with recent work in urban political economy.

Within this subfield, the local built environment is widely understood to result not just from physical conversion of rural to urban land uses but also from local coalitions of business and political elites, or "growth machines," that actively and continually pursue land-use intensification for the profits that it brings them (Molotch 1976; Logan and Molotch 1987). This land-use intensification typically involves using public resources to extend urban frontiers outward into nearby, less-densely settled space and, in the process, further transforming local lands to accommodate the industrial, commercial, transportation, and residential needs of growing numbers of local residents and businesses. Viewed from this perspective, urbanization is not just a function of population concentration but also a politically and economically motivated transformation of local environments into areas of greater land-use intensity. This is especially true in the United States where local governments maintain legal authority over zoning and other land-use decisions and where these powers have become even more prominent over recent decades with the rise of neoliberal policies that have reduced federal development efforts and rendered local growth machines the primary vehicle for transforming local landscapes (Peck and Tickell 2002; Rudel 2009).

Inserting this perspective on urbanization into the emissions discussion not only re-asserts the importance of the built environment but also extends discussion of it to include powerful interests behind the scenes. We hypothesize that these interests seek to intensify existing land uses in ways that unintentionally increase, rather than reduce, local carbon emissions, all else equal. This hypothesis is similar in direction to national and global theories of metabolic rift and the treadmill of production, which contend that urbanization and economic growth more generally bring with them negative environmental consequences. At the local level, we presume that this negative effect results from increased land-use intensity, as indicated by two measures: the share of local lands that have been developed for non-agricultural purposes; and the share of local residents that reside in actual urban-designated places, where land-use intensity tends to be high generally.

Systemic Position

In our framework, population concentration and land-use intensity refer to site-specific conditions of place, but places also have situation-specific characteristics that emerge through ongoing and often unequal interactions with other places (Ullman 1954). In cross-national research this type of situational influence is commonly theorized in terms of a world system comprised of core, periphery, and semi-periphery nations distinguished by different levels of economic, military, and political power (Wallerstein 2004). In analyses of this sort, it is often argued that movement up the world system increases emissions through increased consumption, which comes with and reflects situational power within an expanding global capitalist system (Satterthwaite 2009). In urban sociology, there exists a parallel idea of the urban hierarchy, reflective of unequal power and exchange among places *within* a nation. Our framework asserts that this situational dimension of place has important implications for understanding local effects of urbanization on carbon emissions.

By way of background, the concept of the urban hierarchy has a rich tradition in sociology, dating back to the early 1900s. At that time, McKenzie (1924), an original member of the Chicago School of Sociology, advanced a perspective on urban structure and change in which he argued that social development brings with it increasing specialization of parts and greater centralization of "coordination and control" functions across space (see also Gibbs and Martin 1958). Duncan and colleagues (1960) subsequently refined this concept to document how occupations and industries are hierarchically sorted among places according to their position within a national urban system (for a review, see Wilson 1984). Today's research on "global cities" advances similar claims at the global level (Sassen 1991), underscoring the continued importance of urban hierarchy for understanding the situational dynamics of place within a changing world economy.

Central to these ongoing conceptualizations is the presumption that places positioned towards the top of a given urban hierarchy will have more connections with, as well as control over, other places by virtue of their strategic position within an expanding national and global "space of flows" (Castells 2002). We contend that that this translocal connectivity has local carbon consequences. Specifically, our framework hypothesizes that centrally positioned places located higher up the national urban hierarchy are likely to experience more intensive flows of people, energy and material through their built environments, all else equal. This dynamic occurs because the same network centrality that increases and reflects situational power within larger national and global systems also increases the rate and volume of local metabolic flows, which in turn increase local carbon emissions.

This hypothesis is consistent not only with national-level studies of emissions but also interdisciplinary work on urban scaling. This research demonstrates that cities differ from other living organisms in that their metabolism actually increases as they become larger and more centrally positioned within broader settlement systems (Bettencourt 2010). Here, we understand such urban metabolism generally as flows of energy, people and materials through a place, which helps to increase not only local cultural innovation and economic productivity but also local carbon use and emissions, independent of related processes of population concentration (see Decker et al. [2000]; Kennedy et al. [2007]; Wolman [1965]). We theorize that these local metabolic flows increase in speed and volume with movement up the urban hierarchy through two related processes, or mechanisms. One is by increasing the sheer volume of people and things passing through the local area by virtue of its extensive connections with (and over) other places; another is by extending carbon-based activities into all hours of the night and day to accommodate these increased local flows, that is, by extending the local urban frontier in time as well as space (Melbin 1978). These heightened "flows of place" may be considered the local consequence of a site's relative position within a broader and expanding "space of flows."

Formal Hypotheses

Hypotheses derived from the above framework can be expressed formally as follows:

Hypothesis 1: Local population concentration – measured as a product of demographic size and density of place – *reduces* local carbon emissions.

Hypothesis 2: Local increases in household density, alternative transit use, and commitment to carbon mitigation campaigns mediate, or explain, the negative correlation between local population concentration and carbon emissions.

Hypothesis 3: Local increases in land-use intensity and systemic position that come with population concentration increase local carbon emissions, thereby countering commonly presumed carbon efficiencies of urbanization at the local level.

DATA & METHODS

The ideal dataset to test the above framework and hypotheses would have reliable information on carbon emissions at the local level over time. Such longitudinal data simply do not exist. However, local cross-sectional data for the nation as a whole have recently become available through the Vulcan Project, a collaborative effort of university researchers and the Lawrence Berkeley National Laboratory funded by NASA and the US Department of Energy (Gurney et al. 2009). This project quantified US fossil fuel CO_2 emissions at various scales over the entirety of 2002: from individual factories, power plants, and roadways to neighborhoods, counties and states. This was done by combining data from a full array of emissions monitoring and fuel consumption inventories conducted for local electricity generation, industrial production (including concrete), transportation, and residential and commercial uses. This approach means that local emissions data from the Vulcan project come from actual environmental monitoring rather than from estimates made using population as a predictor. This, in turn, opens new opportunities for investigating population-environment linkages at the local level. Indeed, non-sociologists have already begun to use these data to explore simple correlations between urban classification and per capita carbon emissions at the county-level, affirming that urban-designated counties generally consume less fossil fuel per capita than the national average (Parshall et al. 2010).

The present study digs deeper into this county-level analysis by combining the Vulcan Project's emissions data with population data from the US Census, land data from the National Resource Inventory, climatic data from the Department of Energy, and situational data from the Department of Agriculture to conduct the most thorough sociological analysis to date of local drivers of carbon emissions. We use all counties and county-equivalents in the continental United States (N=3,073) for this study for two reasons. First, counties are the smallest unit of geography for which reliable data on local emissions and related factors are available for the entire country, thereby offering the best and most complete empirical basis from which to examine our framework. Second and relatedly, counties improve our ability to measure multiple dimensions of urbanization beyond the common but incomplete measure of residential concentration in urban-designated places. Use of counties, however, is not without limitation. One shortcoming is that, as subunits of states and nations, counties are more similar institutionally than these larger units, which means that institutional factors emphasized in cross-national research (e.g., neoliberal policies and environmental regulations) will play a less central role in our subnational analyses.

Model Estimation

Because tests indicate significant spatial autocorrelation in our respective outcome variables (described below), we estimate all models in our study using a spatially lagged dependent variable. This variable measures and statistically controls for spatial dependence among neighboring counties, which if left unattended can violate assumptions of independence in regression models (Anselin and Bera 1998; Voss et al. 2006). To compute this spatial lag we first used Geographic Information Systems (GIS) software to construct a queen, first-order contiguity matrix. For each county of observation, this matrix identifies adjacent counties in a movement similar to that of a queen in chess, with neighboring units selected based on shared borders radiating out from the observed unit, or county, on all sides and diagonal corners. From these neighboring units an average value of the dependent variable is computed as a spatial lag. Use of this spatial lag as an independent variable assumes that spatial dependence in the dependent variable operates as a relatively short-distance spatial process whereby proximity increases interaction and similarity among neighboring counties. With this spatial lag, our full model can be expressed generally as follows:

$$\text{Emissions}_i = \beta_1\text{Urbanization}_i + \beta_2\text{Mediators}_i + \beta_3\text{Controls}_i + \rho W\text{Emissions}_i + \varepsilon_i$$

where subscript *i* represents each unit of analysis (or county), while respective βs represent vectors of coefficients for different sets of predictor variables; ρWEmissions represents the spatially lagged dependent variable; and ε_i represents the disturbance term unique to each county. In supplementary analyses (not shown), we also include fixed effects for states in our vector of control variables and report differences where apparent, which is not often.

All regression models are estimated using standard Ordinary Least Squares (OLS), and all non-dummy indicators are converted to natural logarithms. In this form, coefficients of interest indicate the percentage change in the dependent variable in response to a 1-percent change in the respective independent variable. This approach is similar to elasticity models in economics and standardizes respective coefficients for comparison purposes.

Dependent Variables

We estimate two outcomes commonly used to study the carbon efficiency, or intensity, of human activities. The first is emissions per capita, measured as the natural log of *metric tonnes of carbon emitted per person per year* at the county level in 2002. This measure ranges from a low of -0.04 (or 1 metric tonne per person) in Chattahoochee County, Georgia to a high of 6.68 (or 799 metric tonnes per person) in Oliver County, North Dakota. We use per capita rather than total emissions because this is the metric in which untested assumptions about local carbon efficiencies are most strongly articulated, and because regression estimation with per capita emissions yields a more homoscedastic error term than a component method that uses total emissions as the dependent variable

Our second measure of carbon emissions is the natural log of *metric tonnes of carbon emitted per dollar of local gross domestic product (GDP)*, which is widely used to quantify relative economic efficiencies of modernization and associated processes of urbanization (e.g., York et al. 2003a). In fact, urban planners and government consortiums often prefer this measure to per capita emissions because it assesses emissions relative to economic production, which proponents of ecological modernization theory claim reflect environmental efficiencies of agglomeration and technological innovation that rise with local urbanization (OECD 2002; White House 2002). By contrast, proponents of treadmill of production and metabolic rift theories argue that economic development and attendant processes of urbanization tend to increase consumption and waste generation per unit of economic production as more natural resources and energy are extracted and used to fuel larger and more intensive production activities.

Data for both measures come directly from the Vulcan Project described above, which excludes emissions generated by air and sea travel beyond immediate departure and arrival. This restriction means that locally oriented emissions are highlighted in ways that provide a more direct test of hypothesized relationships.

Measures of Local Urbanization

Our framework conceptualizes urbanization as a multidimensional and far-reaching process that occurs everywhere to varying degree and requires a variety of data sources to investigate properly at the local level. Without this conceptualization, prior research misses the fact that landscapes are transformed even in the most rural areas through development of transportation corridors, facilities for extractive industries, power-generation stations, and other forms of fixed capital that Marx long-ago referred to as "urbanization of the countryside." Within this framework, we use data from the 2000 census to measure *population concentration* as the joint, or multiplicative, function of a county's residential population size and density. Conceptually, this operationalization is consistent with classic and contemporary theories of urban ecology, which presume that both factors – size and density – work together to define local levels of urbanization from a sociological perspective (for a review, see Fischer 1995).

Next, we measure local land-use intensity using two variables. The first we call *land urbanization,* which refers to the percentage of all land in a county that is developed for commercial, industrial, transportation or residential purposes. Data for this indicator of the built environment come from the 1997 release of the National Resources Inventory (NRI) published by the US Department of Agriculture. Drawing from a stratified random sample of approximately 800,000 parcels across the country, the NRI identifies developed land as that which has been permanently removed from the rural land base, wherever it is located (see Nusser and Goebel 1997). To control for sampling variability in this measure, we compute and include an *analytic weight* defined as the inverse square root of the average number of acres per observation within the county (see Maddalla 1977: 268). Higher values indicate more observations per acre, and thus greater measurement reliability. By including this measure in our model as a statistical control, we obtain a more accurate estimate of the relationship between land urbanization and carbon emissions, net of measurement variability.

Our other indicator of land-use intensity we call *residential urbanization*, which is measured as the percentage of the local population living in areas considered urban by US government standards. In present context and controlling for population concentration, this conventional measure of "percent urban" becomes an indicator of land-use intensity, reflecting heightened traffic, commerce, and human activity generally. According to the Census Bureau, in order to be designated "urban" a place must reach a population of at least 2,500 and contain at least some areas within it that reach a density of more than 1,000 persons per square mile. At the county level, this variable is conceptually and empirically distinct from local population concentration because the latter provides no direct information about whether a county's population is spread evenly across its land base or concentrated within one or more urban areas within it, where land uses tend to more intensive.

Our final indicator of urbanization is what we call situational or *translocal urbanization*. For this variable we merge two established typologies to create an ordinal scale that identifies each county's relative position within the broader US settlement system. To construct this scale, counties are first divided by metropolitan and non-metropolitan status. For larger metro areas, we use an urban typology developed by Noyelle and Stanback (1983) and updated by Stanback (2002). While some urban typologies have been criticized as being too static and ahistorical, Noyelle and Stanback's classification system is explicitly grounded in recent patterns of economic structure, organizational centrality and change. The result is an improved taxonomy of the US urban hierarchy consisting of eleven distinct levels, or types, of metro areas based on relative economic and demographic position. For measurement purposes, we assign each county to the rank of its respective metro area (e.g., all counties in the New York metro area receive the same top value).

For smaller metro and nonmetro areas not included in the above typology, we use a set of rural-urban continuum codes published by the US Department of Agriculture (USDA 2004). These codes rank counties based on the total size of their urban population and adjacency to metro areas. At the top of this continuum are counties with an urban population greater than 20 thousand and adjacent to a metro area; at the bottom are counties with an urban population less than 2,500 (i.e., completely rural) and *non*adjacent to a metro area. Integrating these codes with Noyelle and Stanback's typology yields an ordinal scale that ranges from a high of 18 for counties in the New York, Chicago, San Francisco and Los Angeles metro areas to a low of 1 for rural, geographically remote counties such as Esmeralda County, Nevada and Petroleum County, Montana. As such, higher values on this scale indicate greater connections with (and over) other places, which we hypothesize increase local metabolic flows that generate carbon waste, all else equal.

Mediating Factors

Three factors are commonly presumed to help explain the carbon efficiencies of population concentration: alternative transit use; household density; and political commitment to emissions reduction campaigns (Walker and Salt 2006). We measure *alternative transit* as the share of workers per thousand who commute by public transportation, cycling or walking, as indicated in the 2000 census. We use the same data to measure *household density* as the average number of persons per household. And, we measure *political commitment to emissions reduction* as a dummy indicator for membership in the global Climate Protection Campaign (CPC) advocated by Local Governments for Sustainability, formerly the International Council for Local Environmental Initiatives (ICLEI 2007). The CPC campaign is a voluntary program of approximately 675 municipalities world-wide dedicated to taking local steps to reduce carbon emissions. The membership list for the United States includes 250 municipalities that account for nearly twenty percent of all carbon dioxide emissions generated annually in the country (Zahran et al. 2008). If a county contains all or part of one of these municipalities, it is coded as 1; otherwise it is coded as 0.

Control Variables

In all models we include statistical controls for socio-economic and climatic conditions emphasized by prior sociological research on greenhouse gas emissions (York et al. 2003a; see also Brown et al. 2008; Gibbs 2000; Murphy 2000). We measure local *affluence* by summing total earnings from all industries in 2002 (from the US economic census) and dividing by the total number of local households to achieve a local approximation of gross domestic product per household unit. We measure *industrialization* as the percentage of the local labor force employed in construction, manufacturing, and mining in 2000. Both indicators are expected to correlate positively with per capita emissions, based on prior research.

County-level data for extreme climatic conditions come from the US Department of Energy (2010), which assigns each county in the United States to a specific type of climatic zone, including “very cold” (e.g., Cass County, ND), “hot-dry” (e.g., Maricopa, AZ), and “hot-humid” (e.g., Miami-Dade, FL). For each of these three extreme climatic zones, we create a separate dummy indicator, with counties in less extreme climates serving as the reference group. Natural science research shows that energy consumption increases with both heating- and cooling-degree days (NOAA 2010); therefore, location in an extreme climatic zone is expected to correlate positively with carbon emissions.

All variables are summarized with data sources and descriptive statistics in Table 1.

[Table 1 about here]

RESULTS

Our framework begins with the assumption that there are four basic dimensions of urbanization that correlate positively with one another at the local level. Table 2 reports bivariate correlations that support this assumption. They show that, without statistical controls, each dimension of urbanization in our framework correlates positively with the others at the $p < .05$ level. Also, computation of an inter-item Chronbach Alpha yields a value of 0.76, indicating a high level of internal consistency among respective indicators. Next, we estimate each variable’s influence on local carbon emissions.

[Table 2 about here]

Model 1 of Table 3 begins by offering an initial test of Hypothesis 1, without mediating factors or other dimensions of urbanization included. Here, results confirm that a significant, *negative* correlation exists between local population concentration and per capita emissions, all else equal ($p < 0.001$). Specifically, the estimated coefficient of -0.05 indicates that local per capita emissions decline by an average of 0.05 percent for each 1-percent increase in population concentration, all other factors in the model held constant. (Note: all subsequent interpretations assume this all-else-equal condition.)

[Table 3 about here]

Next, Model 2 tests Hypothesis 2, that part of the negative effect of population concentration on local emissions is explained by correlated increases in alternative transit use, household density, and political commitment to carbon reduction campaigns. Results provide no support for this hypothesis at the .05-level. Additionally, the estimated coefficient for population concentration changes little from Model 1 to Model 2. These patterns indicate that these commonly presumed mediating factors do not influence local per capita emissions, net of other factors. This is consistent with recent research that shows, for example, that increasing public transit capacity does not actually reduce road congestion (Duranton and Turner, forthcoming).

Next, Model 3 begins to test Hypothesis 3, that other dimensions of urbanization counter the apparent carbon efficiencies of local population concentration. Here it is worth noting that although bivariate correlations in Table 2 raise the possibility of multicollinearity, its relative presence does not violate assumptions of multiple regression, and even in its presence, estimated coefficients remain efficient and unbiased (see O'Brien 2007). The main disadvantages of multicollinearity are that estimated standard errors can become inflated and that they can change from sample to sample, especially if the sample is relatively small. These concerns are minimized here because we analyze the full population of counties from the continental United States providing us with a large number of cases. We also note that collinearity inflates standard errors, but in spite of this fact we find statistically significant results for our key independent variables, and these results are stable across models.[1]

With this mind, Model 3 supports Hypothesis 3 and begins to reveal the paradoxical nature of urbanization's relationship with carbon emissions at the local level. On the one hand, Model 3 shows that when population concentration is statistically disentangled from related dimensions of urbanization, its negative association with per capita emissions increases substantially. This shift in coefficients further supports Hypothesis 1. On the other hand, Model 3 also confirms that, once observed, other processes of urbanization exert significant counter effects on local emissions. Among these counter effects land urbanization presents the most intense tradeoff. Here, results indicate that a 1-percent increase in developed land results in a 0.17 percent increase in local carbon emissions ($p < .001$). Similarly, a 1-percent increase in the share of a county's residents living in urban-designated places results in a 0.03 percent increase in local emissions ($p < 0.01$). Finally, results for translocal urbanization indicate that a 1-percent increase in a place's relative position within the national urban system results in a 0.09 percent increase in local emissions ($p < 0.01$).

These results offer strong support for Hypothesis 3, but some skeptics might argue that this support stems from misspecification of population concentration in our model. Such a critique would argue that this variable's true relationship to local emissions is curvilinear and that in the absence of such proper specification, other measures of urbanization in our model might be "standing in" for this true functional form. Prior sociological research that tests for the presence of an environmental Kutznets curve (EKC) lends some credence to this scrutiny (e.g., Ehrhardt-Martinez 1998), as does research by Andrews (2008), who finds an inverted "U" shape relationship between *population density* and carbon emissions in his case study of New Jersey. To test for this possibility at a broader scale and whether it alters conclusions about Hypothesis 3, we re-specify population concentration in Model 4 to include its squared term.

Results indicate that population concentration does indeed have a curvilinear effect on per capita emissions and that this effect is positive (0.005; $p < 0.001$), indicating that carbon efficiencies associated with population concentration actually *decline* at higher levels. Results also show that introducing this curvilinear effect into our model has little impact on other dimensions of urbanization. Indeed, if anything, statistical evidence for countervailing factors associated with Hypothesis 3 becomes stronger in Model 4, as indicated by decreased p-values for respective coefficients.

To illustrate how these different dimensions of urbanization work alone and in concert, Figure 1 graphs estimated emissions per capita at different levels of population concentration under different assumptions, using results from Model 4 of Table 3. In this figure, Line 1 simulates the effect of population concentration as if it were the only dimension of urbanization operating and as if its effect were linear, as commonly presumed. This simulation is done by setting the variable's squared term and other dimensions of urbanization in Model 4 to zero. Line 2 then simulates the effect of population concentration as if it were the only dimension of urbanization operating and its effect were curvilinear, as observed. This simulation is done by setting the squared term for population concentration to respective values, while holding other dimensions of urbanization at zero. Finally, Line 3 simulates the effect of population concentration as if it were occurring alongside other dimensions of urbanization – which it is, as bivariate correlations in Table 2 affirm. This simulation is done by allowing all four measures of urbanization to vary proportionally together, from low to high observed values. (In all simulations, mediating and control variables are held constant at their population means.)

[Figure 1 about here]

Results illustrate the difference between common assumption, illustrated by Line 1, and empirical evidence uncovered by the present study, in Line 3. This comparison shows that as local population concentration increases, associated carbon efficiencies begin to wane considerably. Figure 1 also indicates that these diminishing environmental returns to population concentration begin to take hold about two-thirds of the way up the observed distribution; thereafter additional population concentration exerts little or no real effect on per capita emissions. In terms of actual places, this means that New York, Los Angeles and San Francisco counties tend to be no more carbon efficient than Dubuque, St. Louis, and San Luis Obispo counties, all else equal. This parity occurs because population concentration's declining carbon efficiencies at higher levels are further reinforced by rising counter-effects of land development, residential intensity, and interaction with other places.

To assess the robustness of these results, we re-estimated a number of supplemental models (not shown). One set repeated all estimations in Table 3 using a robust regression procedure that minimizes the disproportionate influence of outliers by employing a form of weighted least squares regression to downweight cases with large residuals. Prior research indicates that this procedure yields results that are approximately 95 percent as efficient as standard OLS regression (Hamilton 2009), and our results (available upon request) indicate little substantive change from the results reported above. Outliers, in other words, do not unduly influence findings reported in Table 3 and Figure 1. In addition, we re-estimated all models with fixed-effects for states in which counties are located. Again, results (available upon request) do not change substantively from those reported in Table 3 and Figure 1.

Finally, we repeated all analyses for our second dependent variable: emissions per dollar of local GDP. Results appear in Table 4 and tightly parallel those reported for per capita emissions in Table 3. These results lend further support to Hypotheses 1 and 3, and imply that the same simulations illustrated in Figure 1 for demographic accounting of local carbon intensities also hold for economic accounting of local carbon intensities based on emissions per production unit. Similarly, evidence for Hypothesis 2 remains unsupportive. Thus, overall Table 4 provides further confirmation for the conclusion that urbanization is a multidimensional process that exerts countervailing effects on local carbon intensities, regardless of how they are measured.

[Table 4 about here]

CONCLUSION

Urbanization operates at a multiplicity of scales, which has produced a paradox in how we understand its relationship to carbon emissions. On the one hand, population ecologists, urban planners and allied researchers working from local frames of reference have presumed but inadequately demonstrated that urbanization brings with it local carbon efficiencies. On the other hand, sociologists working from national frames of reference have demonstrated that more urbanized societies tend to be less carbon efficient, all else equal. In the present study we have argued that this apparent contradiction stems not just from different levels of analysis – local versus national – but also from limitations in how prior research has defined urbanization as a relatively unidimensional process. To address this shortcoming we advanced an alternative framework for understanding urbanization's relationship to carbon emissions at the local level, one that synthesizes insights from urban and environmental sociology to develop a multidimensional understanding of urbanization and its paradoxical effects on the global environment, via carbon emissions.

To test this framework, we conducted the most thorough sociological study of local drivers of carbon emissions to date. Findings from this study support core elements of our framework. First, they affirm that local variation in urbanization plays a significant role in explaining local variation in carbon emissions per person and per economic output, all else equal. Second, they demonstrate that the same factor widely credited with generating these effects – population concentration – is actually part of a more complex, multidimensional process of urbanization. Our findings also indicate that this complexity has several important features that have gone largely unnoticed until now.

The first feature is that widely presumed scalar efficiencies of population concentration for local carbon emissions decline at higher levels. This is not to say that places with higher population concentrations do not produce fewer emissions per person or production unit; they do, but only up to a point, and then this effect begins to level off, which means that the largest, most urbanized areas of the United States are no more carbon efficient than many smaller urbanized areas positioned further down the urban hierarchy. Our findings also indicate that one reason for this “leveling off” is that that local factors commonly presumed to convert higher population concentration into greater local carbon efficiencies show no such effect. Another reason is that related factors – increased land-use intensity and systemic interaction with other places – exert strong counter influences. These findings have two important implications.

First, research on local emissions that conceptualizes urbanization solely in terms of population concentration or residence in urban-designated places is misleading because it fails to account for the carbon costs of related dimensions of urbanization that accompany population concentration. Acknowledging these countervailing dimensions means viewing urbanization less as a continuum and more as a multidimensional see-saw: As rising population concentration pushes down local per capita and per unit emissions, related processes of land-use intensification and systemic interaction push them up. This means that, when it comes to carbon emissions, urbanization is a balancing act, and while local residents can insert themselves into this act by increasing their use of alternative transit and by supporting local carbon mitigation campaigns, our findings indicate that, as yet, these effort do little to change the social landscape of emissions. This conclusion is consistent with recent discussions of the “paradox of intensification” (Melia et al. 2011) and the “compact city fallacy” (Neuman 2005) in the urban planning literature.

The second implication our study is that prior sociological research conducted at the national level is correct to draw attention to the negative consequences of urbanization for carbon emissions, particularly inefficiencies related to systemic power and conversion of rural to urban land uses. However, this line of research could also be improved by more fully investigating potential environmental efficiencies that can be gained from demographic concentration, at least up to a point. Such efforts would mean moving away from conceptualizing urbanization simply as part of a broader process of modernization to seeing it also as a multidimensional process of eco-social transformation of local lands, with countervailing effects on the global environment.

With these implications in mind, it is worth noting two prime avenues for future research. One involves our inability to distinguish carbon emitted for local consumption (e.g., to power buildings in the same county) from carbon emitted for distant consumption (e.g., to power buildings in other counties). As future research grapples with these measurement complexities, it may become useful to think about what Čapek (2010) calls shifting nature-city boundaries. This perspective suggests that urbanization involves a two-dimensional "metabolic shift" with respect to local carbon emissions. One dimension of this shift, which we have emphasized in the present study, involves a local metabolic shift "upward" as the material production of urbanization at the local level increases metabolic rates by extending carbon-emitting activities into locally available spatial and temporal frontiers, decreasing non-urban residential options and increasing carbon intensity around the clock, day and night.

A second dimension of this shift, which we have left for future research, is a metabolic shift "outward," such that local population concentration displaces carbon-emitting activities elsewhere. To be sure, carbon-intensive activities still occur in heavily urbanized areas but at smaller scales and less prominently per capita than in more rural areas, where we suspect a kind of "rift in reverse" takes place, in which less-developed hinterlands find themselves not only sending more natural resources to growing urban centers but also absorbing more of the carbon-intensive activities that these centers also need but no longer wish to accommodate locally. This possibility is supported by recent world-systems research showing how foreign investment leads to the export of carbon intensive industries to less developed nations (Grimes and Kentor 2003).

Another opportunity for future research involves collection and analysis of additional panels of carbon emissions data at the local level. This effort will be no small feat, but it underscores the point that the present study relied on cross-sectional data to draw inferences about large, multidimensional processes. Assembling longitudinal data on the subject (once they become available) would permit a more dynamic assessment of our analytical framework as well as stronger statistical control of omitted variables that might be operating behind the scenes. Ideally, this data collection and analysis would extend beyond the United States to allow for greater comparative understanding of local processes in the context of shifting institutional settings emphasized by existing cross-national studies of carbon emissions. This extension would be especially useful in Africa and Asia, which have the highest rate of increase in urbanization and the largest urban population in the world, respectively. We look forward to this future research.

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Table 1

VARAIABLE DESCRIPTIONS AND SOURCES (N=3,073)

Variable	Mean	SD	Description	Source
Carbon Emissions per Capita	1.623	0.873	Tonnes of Carbon Emitted per Person, 2002 (natural logarithm)	Vulcan Project (Gurney, et al. 2009)
Carbon Emissions per Dollar of GDP	-7.842	1.019	Tonnes of Carbon Emitted per Dollar of GDP, 2002 (natural logarithm)	Vulcan Project (Gurney, et al. 2009)
Population Concentration	7.475	2.944	Population^2/Total Land Area in Acres (natural logarithm)	US Census Bureau USA Counties; National Resources Inventory
Residential Urbanization	2.932	1.701	Percent of Population Living in Urban Areas, 2000, which consist of core census block groups or blocks that have a population density of at least 1,000 people per square mile and surrounding census blocks that have an overall density of at least 500 people per square mile (natural logarithm)	US Census Bureau USA Counties
Land Urbanization	1.427	0.990	Percent of Land Area (in Acres) that is considered Developed, 1997, which includes roads, railroads, and associated rights-of-way, as well as "built up" areas (natural logarithm)	National Resources Inventory, U.S. Dept. of Agriculture
Translocal Urbanization	6.762	5.501	Position in the Urban Hierarchy: 18=Global Node, 17=National Node, 16=Regional Node, 15=Subregional Node, 14=Functional Node, 13=Government/Service, 12=Manufacturing Node, 11=Government/Military, 10=Resort/Retirement, 9=Other Metro Large, 8=Other Metro Medium, 7=Other Metro Small, 6=Nonmetro With Urban Population 20K+, Adjacent to Metro Area, 5=Nonmetro with Urban Population 20K+, *Not* Adjacent to Metro Area, 4=Nonmetro with Urban Population 2.5-19K, Adjacent to Metro Area, 3=Nonmetro with Urban Population 2.5-19K, *Not* Adjacent to Metro Area, 2=Nonmetro with Urban Population <2.5K, Adjacent to Metro Area, 1=Nonmetro with Urban Population <2.5K, *Not* Adjacent to Metro Area (natural logarithm)	Noyelle & Stanback (1983); Stanback and Grove (2002); US Department of Agriculture (2004)

Affluence	10.434	0.589	Total Earnings from All Industries Divided by Number of Households (natural logarithm)	US Census Bureau USA Counties
Industrialization	3.395	0.299	Percent of Labor Employed in Manufacturing, Construction and Mining, 2000 (natural logarithm)	US Census Bureau USA Counties
Alternative Transit	3.587	0.648	Number of Workers per 1000 Using Public Transit, Cycling, or Walking to Work, 2000 (natural logarithm)	US Census Bureau USA Counties
Household Density	1.262	0.053	Average Persons per Household, 2000 (natural logarithm)	US Census Bureau USA Counties
ICLEI	0.060	0.238	County, or County with a City, Member of ICLEI Local Governments for Sustainability, 2007 (1=Yes, 0=No)	ICLEI (2007)
Very Cold	0.033	0.179	Very Cold Climate Region (1=Yes, 0=No)	US Department of Energy (2009)
Hot Dry	0.140	0.347	Hot-Dry Climate Region (1=Yes, 0=No)	US Department of Energy (2009)
Hot Humid	0.037	0.190	Hot-Humid Climate Region (1=Yes, 0=No)	US Department of Energy (2009)
Aweight	0.045	0.012	Inverse square root of the average number of acres per observation, 1997	National Resources Inventory

Table 2
BI-VARIATE CORRELATIONS

Variable	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
1. Carbon Emissions Per Capita…….....	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2. Carbon Emissions Per Dollar of GDP.	0.82 *	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
3. Population Concentration……………	-0.22 *	-0.43 *	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
4. Residential Urbanization……………	-0.04 *	-0.27 *	0.65 *	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5. Land Urbanization…………………..	-0.18 *	-0.36 *	0.90 *	0.53 *	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6. Translocal Urbanization…………….	-0.12 *	-0.27 *	0.76 *	0.53 *	0.74 *	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
7. Affluence………................................	0.06 *	-0.52 *	0.47 *	0.45 *	0.40 *	0.36 *	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .
8. Industrialization……………………..	0.10 *	0.27 *	-0.45 *	-0.40 *	-0.39 *	-0.43 *	-0.35 *	1	. . .	. . .	. . .	. . .	. . .	. . .
9. Alternative Transit…………………..	0.02	-0.07 *	-0.12 *	-0.07 *	-0.13 *	-0.10 *	0.14 *	-0.30 *	1	. . .	. . .	. . .	. . .	. . .
10. Household Density………………….	0.00	0.00	0.16 *	0.18 *	0.08 *	0.27 *	0.13 *	-0.03	-0.13 *	1	. . .	. . .	. . .	. . .
11. ICLEI………………………………..	-0.09 *	-0.21 *	0.38 *	0.20 *	0.36 *	0.35 *	0.25 *	-0.29 *	0.16 *	0.02	1	. . .	. . .	. . .
12. Very Cold…………………………....	0.08 *	0.05 *	-0.15 *	-0.11 *	-0.15 *	-0.12 *	0.00	-0.06 *	0.18 *	-0.15 *	0.00	1	. . .	. . .
13. Hot Humid………………………….	0.02	0.05 *	0.07 *	0.07 *	0.07 *	0.05 *	-0.02	-0.12 *	-0.19 *	0.18 *	-0.02	-0.07 *	1	. . .
14. Hot Dry……………………………..	0.05 *	0.04 *	-0.08 *	0.02	-0.10 *	-0.01	0.02	-0.07 *	-0.01	0.13	0.01	-0.04 *	-0.08 *	1

* $p < 0.05$

Table 3

OLS REGRESSIONOF PER CAPITA CARBON EMISSIONS (N=3,073)

	Model 1		Model 2		Model 3		Model 4	
	b	SE	b	SE	b	SE	b	SE
Population Concentration……	-0.054***	0.007	-0.057***	0.007	-0.141***	0.015	-0.201***	0.024
Population Concentration ^{2}….	. . .	. . .	. . .	. . .	. . .	. . .	0.005**	0.001
Residential Urbanization…….	. . .	. . .	. . .	. . .	0.034**	0.013	0.043**	0.013
Land Urbanization…………...	. . .	. . .	. . .	. . .	0.177***	0.037	0.123**	0.040
Translocal Urbanization……..	. . .	. . .	. . .	. . .	0.092**	0.030	0.094**	0.030
Alternative Transit…………..	. . .	. . .	-0.033	0.027	-0.007	0.027	-0.059	0.031
Household Density…………..	. . .	. . .	-0.052	0.293	-0.138	0.304	-0.196	0.304
ICLEI……………….……..	. . .	. . .	-0.019	0.068	-0.021	0.068	-0.070	0.070
Affluence…………………….	0.268***	0.029	0.275***	0.029	0.266***	0.030	0.269***	0.030
Industrialization…….………..	0.211***	0.057	0.178***	0.063	0.233***	0.064	0.229***	0.064
Very Cold………………….	0.114	0.083	0.123	0.085	0.151	0.085	0.166†	0.085
Hot Humid………………....	0.072	0.044	0.060	0.045	0.049	0.045	0.046	0.045
Hot Dry……………………...	0.026	0.080	0.019	0.081	0.007	0.081	-0.057	0.083
Analytic Weight……………..	-3.143*	1.272	-3.111*	1.276	-4.482**	1.326	-4.197**	1.326
Spatial Lag………………...	0.468***	0.034	0.443***	0.467	0.436**	0.528	0.428***	0.034
Constant………………….…..	-2.124***	0.388	-1.875***	0.529	-1.705**	0.528	-1.256*	0.545
Adjusted R^2………………….	0.141		0.140		0.153		0.156	
Mean/Max VIF………………	1.26/1.77		1.33/2.16		2.42 /8.70		4.86/22.86	

† $p < 0.1$, * $p< 0.05$, ** $p< 0.01$, *** $p <0.001$

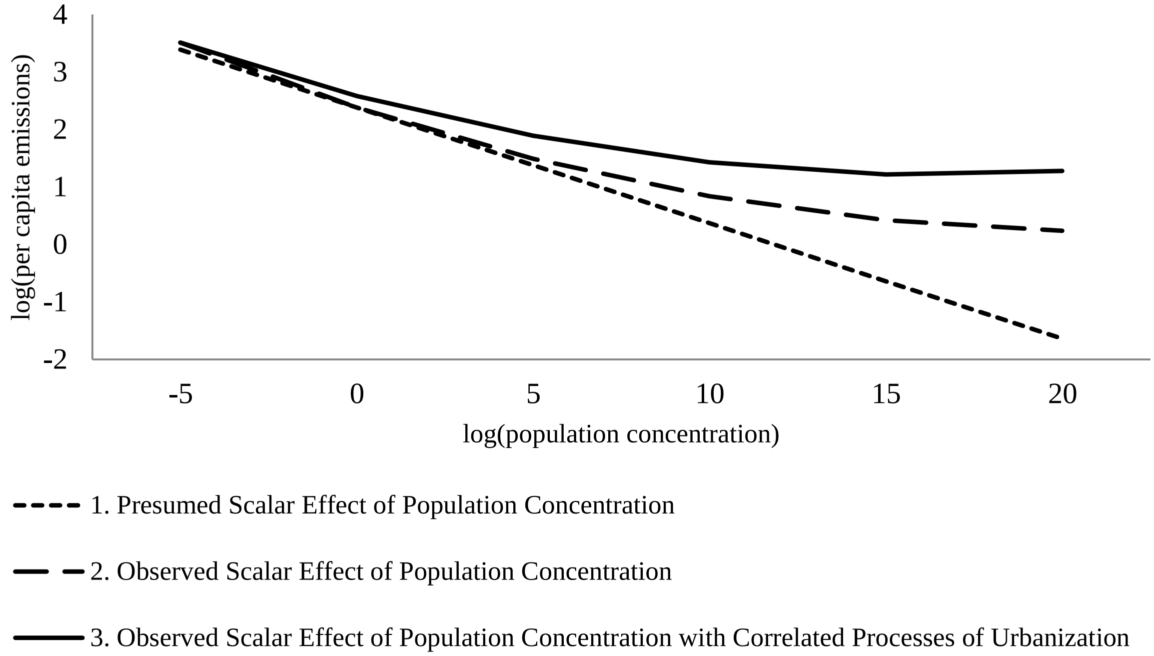
Table 4

OLS REGRESSION OF CARBON EMISSIONS PER DOLLAR OF GDP (N=3,073)

	Model 1		Model 2		Model 3		Model 4	
	b	SE	b	SE	b	SE	b	SE
Population Concentration……	-0.045***	0.007	-0.051***	0.007	-0.139***	0.015	-0.187***	0.024
Population Concentration ^{2}….	. . .	. . .	. . .	. . .	. . .	. . .	0.004**	0.001
Residential Urbanization…….	. . .	. . .	. . .	. . .	0.039**	0.013	0.046**	0.013
Land Urbanization…………....	. . .	. . .	. . .	. . .	0.177***	0.037	0.133**	0.040
Translocal Urbanization……..	. . .	. . .	. . .	. . .	0.097**	0.030	0.094**	0.030
Alternative Transit…………..	. . .	. . .	-0.033	0.027	-0.006	0.027	-0.048	0.031
Household Density…………..	. . .	. . .	1.434***	0.293	1.334***	0.304	1.288***	0.304
ICLEI………………….……..	. . .	. . .	-0.022	0.068	-0.021	0.068	-0.061	0.070
Affluence…………………….	-0.749***	0.029	-0.755***	0.029	-0.766***	0.030	-0.763***	0.030
Industrialization…….….……..	0.186**	0.058	0.128*	0.063	0.188**	0.063	0.185**	0.063
Very Cold………………….	0.063	0.085	0.117	0.085	0.147†	0.085	0.158†	0.085
Hot Humid………………....	0.126**	0.044	0.074	0.045	0.064	0.045	0.061	0.045
Hot Dry……………………....	0.089	0.080	0.021	0.081	0.008	0.081	-0.043	0.083
Analytic Weight……………..	-3.212*	1.277	-2.805*	1.275	-4.106**	1.324	-3.876**	1.326
Spatial Lag………………...	0.475***	0.034	0.465***	0.034	0.431***	0.034	0.425***	0.034
Constant…………….………..	-0.986***	0.389	-2.362***	0.529	-2.168***	0.528	-1.806**	0.545
Adjusted R^2………………….	0.365		0.370		0.380		0.381	
Mean/Max VIF………………	1.26/1.77		1.33/2.16		2.42 /8.70		4.86/22.86	

† $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 1
SIMULATIONS OF PER CAPITA CARBON EMISSIONS BY LOCAL RATES OF URBANIZATION



Source: Table 3, Model 4.

Notes: Respective lines are simulated as follows:

1. The main effect of population concentration is allowed to vary but not its quadratic effect or the effect of other, correlated dimensions of urbanization, which are set to zero. All other factors are set to population means.

2. The main and quadratic effects of population concentration are allowed to vary but not the effects of other, correlated dimensions of urbanization, which are set to zero. All other factors are set to population means.

3. The main and quadratic effects of population concentration are allowed to vary, and other, correlated dimensions of urbanization are set to increase proportionally, from low to high observed values. This simulation is the most consistent with results from Model 4 of Table 3, which provides the best overall fit to the data.