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Urban density and the metabolic reach of metropolitan areas: A panel analysis of per capita transportation emissions at the county-level

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ABSTRACT

We engage a tension in the urban environment literature that positions cities as both drivers of environmental destruction and loci of environmental protection. We argue that the traditional binary view of cities as either harmful or beneficial is too simplistic; we advance a more nuanced understanding of cities to study their internal and external metabolic effects in terms of carbon emissions from on-road transportation at the county-level across the continental United States between 2002 and 2007. First, utilizing satellite imagery from the National Land Cover Database, we create a novel measure of population density by quantifying the number of people per square mile of impervious surface area. Second, we develop a measure of metropolitan adjacency from the rural classifications datasets published by the USDA. In spatial regression models, we find that while higher density reduces emissions, counties that are geographically isolated from metropolitan areas actually have lower per capita emissions, *all else equal*. We elaborate on the conceptual, methodological, and practical implications of our study in the conclusion.

1. Introduction

Cities drastically change local environments, requiring ample resources for infrastructure and are prone to air, water, and land pollution, heat islands, and concentrations of greenhouse gas emissions (McNeill, 2000; Intergovernmental Panel on Climate Change IPCC 2007; Melosi, 2010). Nevertheless, not all cities are equally destructive (Rees and Wackernagel, 1996; McNeill, 2000; Moore et al., 2013). Havana, Cuba, for instance, exhibits that urban spaces can be reorganized for agriculture and reforestation (Koont, 2011; Ergas, 2014). In addition, Owen (2009) suggests that places like Manhattan are home to some of the most energy efficient people in the United States because they drive less, live in smaller dwellings, and live closer to amenities. Like Owen, many environmental scholars argue that urban density offers potential solutions by harnessing the spatial density of people for energy efficiency and social movements (Rees and Wackernagel, 1996; Mol, 2001; Keil, 2003; Portney, 2003; Mazmanian and Kraft, 2009; Satterthwaite, 2009, 2010; Glaeser, 2011). Thus, as some researchers have observed (Rees and Wackernagel, 1996; Keil, 2003), there is a paradox presented in this literature: cities are recognized as the

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sources and centers of ecological problems but are indispensable for the development of sustainable solutions to these problems. This paper seeks to address this paradox by examining the metabolism of urbanization as a multidimensional force behind fossil fuel use measured in terms of carbon emissions from transportation.

To that end, we highlight an implicit framework underlying the socio-environmental literature that suggests that urbanization entails both *internal* and *external* changes with countervailing metabolic consequences. The term *socio-ecological metabolism* has a long history in urban environmental scholarship (Foster, 1999; Wachsmuth, 2012; Wolman, 1965; see also Fischer-Kowalski, 1998); it generally represents the flow of natural resources inside and outside the boundaries of urban spaces (Su et al., 2012: 70). We discuss these consequences in greater detail below specifically in terms of transportation carbon emissions. Here we introduce briefly our general empirical approach. Representing *internal change*, we obtain satellite imagery (Fry et al., 2011) to create a novel measure of density based on impervious surface area (rather than total land area); we argue that this approach yields a more explicit measure of density, the effects of which are compared to another variable using data from the US Census on "urban" populations. Representing *external change*, we utilize data on metropolitan adjacency from two of the USDA's (2013) rural classifications datasets: the Urban Influence and Rural-Urban Continuum Codes. At the county-level, these internal and external measures are incorporated into spatial panel models using group-mean centering (Firebaugh et al., 2013: 120; see also Allison, 2009 and Sjölander et al., 2013) to estimate the within- and between-unit effects of urbanization on transportation emissions per capita between 2002 and 2007. We elaborate on the empirical and analytical details below in the methods section; for now, suffice it to say that in our analysis we examine both time-variant and time-invariant factors to highlight the internal and external metabolic consequences of cities.

The layout of the paper is as follows: First, we review the environmental literature that frames the internal and external metabolic dimensions of cities as differential forces behind transportation carbon emissions, also discussing two theoretical perspectives highlighted in recent urban scholarship in order to formulate a set of hypotheses. Then, we describe the data and analytic techniques we use to test these hypotheses, with an emphasis on the group-mean centering technique for panel models. Results from these models show that first *population density* (i.e., the number of people per square mile of impervious surface area) is a more robust measure than *percent urban* and second, while density reduces emissions, counties that are geographically isolated from metropolitan areas actually have lower per capita emissions, *all else equal*. In the conclusion, we elaborate on the conceptual, methodological, and practical implications of our study.

2. Literature review and theoretical frameworks

The process of urbanization entails a range of environmental consequences, which are evident both within the boundaries of cities and extending well beyond city limits. We conceptualize these separate loci of environmental transformation in terms of *internal* and *external* change. *Internally*, urban dwellers can be exposed to air, water, land, and noise pollution as well as overcrowding and traffic congestion (Ponting, 2007; Penna, 2010), but cities can also provide the opportunity for the efficient use of resources, thereby minimizing environmental impact (Owen, 2009; Satterthwaite, 2009, 2010; Melosi, 2010; Glaeser, 2011). *Externally*, dense living spares non-urban land from sprawling development (Ehrhardt-Martinez, 1998), but cities must draw on natural resources from distant places in order to feed, clothe, and house urban residents (Rees and Wackernagel, 1996). Moreover, big cities, especially large metropolitan areas, influence human activities and behavior in settlements and localities outside the boundaries of, and spatially removed from, the metropolitan area itself (e.g., Neal, 2011).

Environmental scholars use the term socio-ecological metabolism to represent the internal and external flow of natural resources through the city and propelled by the city outside of its boundaries (Fischer-Kowalski, 1998; Foster, 1999; Wachsmuth, 2012; Wolman, 1965). In the urban metabolism literature, empirical researchers have long conducted material flow analyses to quantify the amount of natural resources flowing into and away from cities (see Decker et al., 2000; Kennedy et al., 2007). Furthermore, environmental scholarship on metabolism has emphasized the urban connection to the carbon cycle generally and fossil fuel use in particular (see Pataki et al., 2006; Marcotullio et al., 2014). On that note, while we neither conduct a material flow analysis nor examine the carbon cycle in its entirety, our study draws on the metabolism concept in order to examine how the distinct features of cities might differentially impact the flow of fossil fuel used for transportation (measured in terms of carbon emissions per capita). We argue that cities have an expansive metabolic reach, influencing the level of transportation carbon emissions not only inside but also outside the boundaries of the city itself.

To discuss these internal and external consequences, we draw on different theoretical frameworks from the urban-environmental literature, participating in the exchange between *urban political economy* and *ecological modernization* (e.g., Elliott and Clement, 2015; Keil, 2003; Lankao, 2007; Nielsen, 2014). Here we review briefly these theoretical frameworks, in light of the internal and external metabolic consequences of urbanization. Generally speaking, these two perspectives can be distinguished by their relative focus on the inward versus outward impacts of cities. Whereas the ecological modernization approach *tends* to emphasize the internal efficiency of dense urban living, the political economy approach *tends* to emphasize the socio-environmental pressures that cities place on external localities and resources. To be clear, these distinct research foci are not exclusive; studies in the urban political economy tradition have looked at the ways in which social stratification structures exposure to pollution *within* urban areas (e.g., Crowder and Downey, 2010), and previous ecological modernization research has examined the potential for urbanization to relieve stress on the *external* environment (e.g., Ehrhardt-Martinez, 1998). Nevertheless, this general distinction is apparent and constructive; not only is it discernible in the literature but also helps to illuminate the paradoxical claim we mentioned in the