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Location matters: Population density and carbon emissions from residential building energy use in the United States

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ABSTRACT

We study how carbon emissions from U.S. housing stock change with urban location and associated population density, using data from the U.S. Residential Energy Consumption Survey (RECS) and American Community Survey (ACS) in a mediation model to quantify direct and indirect effects of population density on carbon emissions. Urban living in the United States today is generally associated with lower levels of residential carbon emissions, with some of the more significant effects being indirect. For example, more densely populated areas are associated with decreased housing size, which in turn decreases carbon emissions. One of the largest indirect effects observed is from the prevalence of natural gas heating in urban areas. We also observe large indirect effects from the urban prevalence of attached and multi-family housing. A policy question is whether emissions-reducing housing choices could be effectively promoted in non-urban areas.

1. Introduction

Urbanization is one of human history's most enduring trends. Today about 52% of the world population resides in urban areas, with that proportion expected to rise to 67% by 2050 [25]. At the same time, climate change has become the world's most urgent environmental problem. Cities clearly have some environmentally positive aspects, for example in reducing land use and automobile usage [15,19]. Net environmental effects of urban living depend on urban impacts on a range of activities, including human transportation, transportation of goods, provision of housing, water provision and treatment, solid waste generation and disposal, etc. In this study we examine the connection between urban location and climate change through residential building carbon emissions in the United States, considering whether and to what extent urban location correlates with changes in housing carbon emissions. We use population density as a continuous measure of urbanization across the entire rural-urban continuum.

Our primary data from the 2009 U.S. Residential Energy Consumption Survey (RECS) suggest that urban location is associated with modest differences in residential carbon emissions [3]. Table 1 shows the 10th, 50th, and 90th percentiles of per-capita residential building carbon emissions in census-defined urban and nonurban (rural and suburban) areas, with nonurban emissions being greater at each of these percentiles. By combining the RECS data with data from the American Community Survey (ACS) 2005–2009 5-year sample, we are able to derive more precise information about urban location and carbon emissions than can be ascertained from either dataset alone. We use the two datasets in a mediation model to capture indirect effects of urban location. For example, urban location is correlated with house size, and house size affects carbon emissions. Urban location thus affects carbon emissions indirectly through the mediator variable of house size. An ordinary least squares (OLS) model would estimate the effect of urban location on carbon emissions while holding house size constant, missing an important aspect of the relationship. Estiri [7] uses a similar approach to estimate indirect effects of household characteristics. For example, income also affects house size, which in turn affects carbon emissions.

1.1. Urban location effects on housing carbon emissions

There are several paths through which urban location is expected to affect housing carbon emissions. These can be classified as direct impacts, indirect impacts, and transfers of emissions from one location to another.

Direct impacts are those caused by the urban environment itself. For example, increased housing density means that buildings are

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Table 1
U.S. per-capita household CO_2 emissions in metric tons, by urban and nonurban (suburban and rural) area.

	Urban	Nonurban
U.S. household sample (number)	9656	2427
10th percentile (metric tons CO_2)	1.31	2.00
Median (metric tons CO_2)	3.34	4.41
90th percentile (metric tons CO_2)	7.48	9.34

Source: RECS.
n = 12,083.

located in closer proximity to one another. This creates a heat-island effect, where the spaces between buildings are warmer than they would be otherwise, increasing cooling loads in summer and decreasing building heating loads in winter. Similarly, denser building placement may reduce the need for residential exterior lighting, as more light is received from adjacent buildings and public ways. Though there are several such direct pathways, these effects are not necessarily large [9]. If one were to take a given house and change its location from a congested urban street to a remote rural field, we would not expect to see much change in carbon emissions from the house itself (apart from changes in occupant behavior like driving, which we do not consider here).

Table 2 shows differences in potential mediator variables for indirect effects. House size is smaller in urban areas because of both fewer rooms per capita and smaller average room sizes (Table 2). We hypothesize two possible reasons for the connection between urban density and house size. First, urban development implies the existence of nearby alternative spaces, for example nearby restaurant space, which may provide at least a partial substitute for space in the home. This is one reason urban residents could have less space in their homes and have lower carbon emissions. Second, housing space is generally more expensive in urban areas, and all else equal, a higher price for a good should imply reduced consumption. Some houses also have ancillary spaces including basements, attics, and garages, which again are less common in urban areas (Table 2). Even if such space is not heated and cooled, such ancillary structures are generally associated with some energy consumption (e.g. lighting) and related carbon emissions.

Housing configuration is also systematically different in densely populated areas (Table 2). Urban housing units are more likely to be attached to other units, either in semi-detached configurations where common walls are shared, or in apartment buildings where floor and ceiling surfaces are also shared. When housing units share common surfaces they have lower ratios of exterior surface areas to useable floor areas, reducing heating and cooling loads and associated carbon emissions. The same effect may occur in taller buildings: all else equal, a typical-size 2-story house will consume less energy than a single-floor house with the same floor area, since the 2-story house has less exterior area exposed to the weather. These are again indirect effects of urban location, since the direct effect of the urban environment is on housing configuration, and this configuration in turn affects housing carbon emissions.

In addition, urban location has an indirect effect on the mixture and carbon intensity of energy sources. As shown in Table 2, U.S. urban areas are much more likely to have natural gas available, given that this requires a pipeline infrastructure. Houses in less densely populated areas often use propane gas or fuel oil for heating, both of which have higher carbon contents than natural gas, and are thus responsible for more carbon emissions. Some houses also use electricity or electric heat pumps for heating, the carbon intensity of which varies across U.S. regions and with heat pump efficiency.

In addition to direct and indirect effects, urban location may create transfers of energy use from households to other locations. In contrast with an indirect effect that changes real energy usage, a transfer just changes whether we observe the energy usage in the home. For example, Table 2 shows that doing laundry and cooking at home are somewhat less likely in urban areas. Presumably this means that the energy and carbon emissions related to these tasks occur in other places. In some cases, this may result in efficiencies, e.g. if commercial laundries are more efficient than home washing machines. But apart from any such efficiency gains, transfers do not represent real reductions in carbon emissions attributable to a household. We test for the presence and significance of such transfers in the model described below.

1.2. Previous studies

Two studies based on RECS 1993 data [14] and RECS 2005 data [16] found location in a central city to be an insignificant predictor of total energy use (electricity plus heating fuels), but a significant and negative factor for electricity use. A Canadian study established that per-capita, non-industrial electricity use declines with population density in the Canadian cities studied, though the magnitude of the density effect was not large [17].

Glaeser and Kahn [12] researched this question using census energy data rather than RECS data, based on a larger sample size and availability of the respondents' cities of residence in the data set. A problem with the census data is that only energy expenditure is reported in the census, and usage must be estimated from energy prices. Also, there is no energy expenditure for renters who do not pay directly for energy use (in our RECS data, 11% of the sample do not pay directly for heat), so Glaeser and Kahn [12] used RECS data to estimate energy use for such renters. Energy use was found to vary significantly by metropolitan area, even after adjusting for climate variables, but the effect of population density was not explicitly modeled.

Ewing and Rong [9] develop the concept of direct and indirect urban effects, studying the influence of urban heat islands and

Table 2
U.S. nonurban and urban locations, mean values of potential mediator variables for CO_2 emissions.

	Variable	Nonurban		Urban		Likely urban effect on CO_2 emissions
		mean	std. dev.	mean	std. dev.	
1.	Dwelling rooms per occupant	3.12	1.76	2.81	1.69	decreases
2.	Detached dwelling, proportion	0.93		0.63		decreases
3.	House age, years	29.26	25.11	40.12	24.26	increases
4.	Dwelling has gas heat, proportion	0.23		0.55		decreases
5.	Household has clothes washer, proportion	0.95		0.80		transfers
6.	Hot meals cooked per week	8.55	5.48	8.34	5.75	transfers
7.	Building floors	1.37	0.53	1.87	2.24	decreases
8.	Average room size, m^2	28.96	13.94	25.79	12.27	decreases
9.	Household has ancillary space, proportion	0.79		0.67		decreases

Source: RECS.
n = 12,083.