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Research Paper

Urban form and air quality in the United States

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HIGHLIGHTS

- The relationship between urban spatial structure and air quality is explored.
- Fragmentary urban form is associated with low air quality.
- Larger areas of forests in a county are associated with higher PM2.5 exceedance days.
- Proximate forests to urban areas reduce the number of AQI exceedance days.

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ABSTRACT

In this paper, we investigate the relationship between urban spatial structure and air quality in the United States. By using urban landscape metrics framework, we empirically examine whether fragmentary and sprawling urban patterns are associated with low air quality. We develop an algorithm to correct for biases within the urban landscape metrics in the United States. Controlling for demographic variables and economic activity, we find a strong relationship between the type and pattern of development and pollutant levels. The finding is not biased by the presence of relatively rural counties in the dataset suggesting that paying close attention to the urban form might have some implications for air quality.

1. Introduction

The configuration of urban development has long been known to be a major cause of poor air quality (Stone, Mednick, Holloway, & Spak, 2007). Previous research has demonstrated the relationship between sprawl indicators such as density, street network, and leap-frog development, and air quality (Cervero & Kockelman, 1997; Frank & Pivo, 1994). However, the exact relationship between development patterns and air quality has been elusive due to difficulties in quantifying patterns or using indicators poorly suited for spatial analysis (Borrego et al., 2006). By using remote sensing land cover data we are better able to tease out the impacts of specific development characteristics such as fragmentation and leap-frog development. Patterns of configuration represented through urban landscape metrics offer alternatives to typical characterizations that use population distribution while simultaneously overcoming some of their spatial limitations (Burchfield, Overman, Puga, & Turner, 2006; Kaza, 2013). Furthermore, the relationship between urban settlement patterns and air quality is understudied in relatively underdeveloped areas. In this paper, we study the relationship between air quality and urban form in a more comprehensive manner than before in the United States. We find that poor air quality and urban fragmentation are related in all types of counties and not just in metropolitan regions. Using land cover data we are also able to explore the mitigating potential of forest land cover that are proximate to urban areas.

Land cover data is an attractive way of measuring urban patterns because it overcomes the fundamental limitations inherent to measures that rely solely on demographic data. Most research on this topic has been limited in terms of coverage and spatial continuity. Most sprawl indices and urban form metrics are calculated at the Metropolitan Statistical Area (MSA) level missing both rural areas outside MSAs and finer grain patterns within them. Comprehensive characterizations take into account facets such as population density, continuity, concentration (Galster et al., 2001) or land use mix and street accessibility (Ewing, Pendall, & Chen, 2003). These characterizations are geographically limited to specific regions due to data availability and computational considerations.

Unlike demographic data, land cover indicators provide comprehensive data of both urban and rural areas for the conterminous United States. As land cover data is derived from satellite imagery, continuous monitoring is possible. Landscape metrics characterize urban development independent of demographic changes as well

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as providing information about non-urban uses. Accordingly, we can then test the composition as well as configuration of urban patterns in both urban and non-urban land cover information. We take advantage of this to explore the potential importance of mixing of multiple types of land uses.

Forests in close proximity to urban development are a potentially important factor in determining air quality. Forests contribute to air quality conditions by both mitigating and producing Ozone precursor emissions. Trees are estimated to remove 0.7 million metric tons of pollutants per year in the United States (Nowak, Crane, & Stevens, 2006). Precursor compounds (VOC & NOX), which form Ozone are also produced by biogenic sources. As tree cover and urban area are simultaneously captured in satellite data and fragmentary urban form could be associated with interspersed forest cover, the degree to which the two are mixed may be relevant to air quality.

Landscape metrics often used to study habitat fragmentation can also be used to characterize urban form. Unlike traditional landscape metrics that use natural areas as their main focus, urban landscape metrics depend on identifying patches of contiguous urban areas. Once these patches are identified, various metrics such as number, mean patch area, etc. can be readily calculated. Urban landscape metrics have been used to monitor patterns of growth at a metropolitan level but their use has been limited to select geographies (Bereitschaft & Debbage, 2013; Buyantuyev, Wu, & Gries, 2010; Seto & Fragkias, 2005) or was marred by data quality issues (Kaza, 2013). In this paper, we correct some of the issues associated with using raw land cover data within the United States while testing two prevailing hypotheses: (1) more fragmented and expansive patterns of development are correlated with bad air quality than more contiguous configurations, and (2) the relative mixing of urban and forest land impacts air quality.

2. Background

Fragmentary and dispersed patterns of urban development, without high quality transit are associated with high automobile use, longer trip lengths and subsequent air quality problems. This connection forms the basis for most emissions modeling (Borrego et al., 2006). However, urban patterns also affect air quality. Impervious surface cover are associated with Ozone (O_3) formation (Taha, 2008), building configurations with pollutant dispersal (Sini, Anquetin, & Mestayer, 1996) and leapfrog development with increased NO_2 (Bechle, Millet, & Marshall, 2011).

For example, Hartford County, CT and Fulton County, GA are comparable in terms of population, metropolitan population, density, and urban area. They are likewise comparable according to the sprawl index criteria of Ewing et al. (2003). Fulton, however, generates significantly more air pollutants and suffers a greater number of days with excessive Ozone levels annually. We hypothesize, as previous modeling studies have (Martins, 2012), that the difference in air quality outcomes can be explained, in part, by the differences in urban development patterns.

The few existing empirical studies that examined the relationship between urban patterns and air quality focused primarily on metropolitan regions. In their study of over 100 metropolitan areas, Clark, Millet, and Marshall (2011) found that characteristics such as population centrality explain as much variation in pollutant concentration as climate. In a similar study on O_3 exceedances, sprawling regions are associated with higher mean annual exceedances after controlling for precursor emissions (Stone et al., 2007). However, the urban form characteristics used in these studies are limited to measures based on demographic (Bento, Cropper, Mobarak, & Vinha, 2005; Downs, 1999; Lopez, 2014) or employment data (Glaeser, Kahn, & Chu, 2001) within the metropolitan regions. Bereitschaft and Debbage (2013), an exception, use urban landscape metrics to characterize the relationship between emissions and urban form based on landscape metrics, however, use modeled emissions as the dependent variable rather than air quality.

There are many advantages to using land cover data to calculate the metrics of urban form. First, a comprehensive database that covers both urban and rural areas for the conterminous United States is readily available. Continuous monitoring is possible and the data are updated on a continuous five-year cycle through satellite imagery. Second, we can account for the intermixing of different land cover types without focusing solely on urbanized area. Tree cover is an important mitigating factor for many types of emissions (Escobedo & Nowak, 2009; Zipperer, Sisinni, Pouyat, & Foresman, 1997). Tree cover and urban area are simultaneously captured in satellite data; it is possible to explore how fragmentary urban form could be associated with interspersed forest cover and have impacts on air quality. Third, many areas in the US are losing population, especially in the rust belt and rural counties, while the total developed area in the county remains the same or is increasing. This is due to disconnect between urbanized land and population dynamics. Urbanization is largely irreversible while people and jobs are mobile; metrics that are characterized only by demographic and economic variables at any given time are less likely to capture the phase difference between urban land conversion and economic and demographic changes in a place. While there are some disadvantages that we will discuss later, we find using satellite data to describe urban patterns is useful and complementary to standard accounts.

To demonstrate the differences in the urban form indicators of various studies, we compared the performance of various MSAs. Only a few metropolitan areas are persistently present in the top ten sprawled areas according to various indices (see Table 1), the most prominent being Atlanta and Miami MSA. While the indicators were calculated using different datasets and at different time points, this shows how land cover data and demographic data are complementary to describe the urban spatial structure. Even within a single metropolitan area there are significant differences. For example, within the New York MSA gross county level population density ranges from 166 to 27,470 (per sq. km) suggesting significant variation within the urban form. Similarly, the number of days with bad air quality ranges from 4 to 19 within the counties in the New York MSA. Thus, while Table 1 refers to MSAs, the rest of this study focuses on counties.

We begin by describing the various data sources and data processing steps to arrive at a county level sample. We then briefly describe the state of air quality and urban morphological indicators in the US in the last decade. The results of the empirical analysis are discussed with some caveats and we conclude with further questions this research raises.

3. Data description & methods

Our cross-sectional analysis uses data circa 2006, compiled from a number of sources for the conterminous United States. We restrict our attention to the Criteria Air Pollutants (CAP) as defined by the Clean Air Act. In particular, we study O_3 and particulate matter (PM2.5) in greater detail due to their acute health impacts. We use the number of days Air Quality Index (AQI) exceeds 100 as a measure of air quality in a county.

To compute the Gini coefficient of population density (at a block group level), we used population data from 2000 Census available in Almquist (2010). This coefficient measures centrality and ranges from 0 (uniform density) to 1 (highly concentrated density). We use county character (Rural, Mixed Rural, Mixed Urban and Urban) as