Is Urbanization Good for the Climate? A Cross-County Analysis of Impervious Surface, Affluence, and the Carbon Intensity of Well-Being

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Abstract
We contribute to literature exploring the socioecological impact of urban development as a multidimensional project, one in which changes to landscape features complement changes in demographic and administrative measures to co-constitute the socioecological impact of urbanity. We use a random coefficients modeling approach to examine U.S. relationships between the intensity of impervious surface within a county, population density in impervious areas, and carbon intensity of well-being (CIWB)—here constructed using industrial emissions. We then explore the moderating association that another component of social settlement patterns, household median income, has on the impervious surface—population density—CIWB nexus. Findings suggest that landscapes featuring greater development of impervious surface are associated with increased CIWB. Further exploration indicates that income acts to attenuate the association of urban space and CIWB. Ultimately, we argue that such attenuation indicates that more affluent areas are able to shift production-based processes associated with urban forms to less affluent areas.

Keywords
impervious surface, carbon intensity of well-being, CIWB, population density, structural human ecology

Introduction
Climate change, drastic disruptions in economic and cultural structures, and neoliberal globalization’s compression of space and time have combined to generate global shifts in the location of populations that have spurred urban development. These social and environmental forces also have led to transitions in the forms such urbanized spaces take (United Nations Population Fund 2007, 2014). Meanwhile, recent population projections have indicated that by midcentury, the global population will grow beyond 9 billion people (United Nations Population Fund 2012) and that the patterns of consumption that support this ballooning population are increasingly unsustainable (Intergovernmental Panel on Climate Change 2018; Jorgenson and Givens 2015; McGee et al. 2017; Owen 2009; Satterthwaite 2010).

The common thread running through current work on the socioenvironmental outcomes of urban change, regardless of divergences, is that urbanization should be understood as simultaneous transformations in where populations are located, complexes of demographic, socioeconomic, and structural/infrastructure relations that constitute urban space, this literature has yielded important, if at times contradictory, results regarding the broader role that urbanization plays as a driver of environmental change and social inequality (e.g., Ehrhardt-Martinez et al. 2002; Elliott and Clement 2014a, 2014b; Ergas, Clement, and McGee 2016; Liddle 2013; McGee, Clement, and Besek 2015; McGee et al. 2017; Owen 2009; Satterthwaite 2010).

Today, scholars are focusing on how and why these trends in the size, organization, and location of the world’s population affect the intensity of urban development, as well as on better understanding the relationship between such intensification and environmental harm. Largely focusing on the

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their density, the intensity of landscape use, and the distribution of wealth and other social resources. In particular, recent research (e.g., Ergas et al. 2016) has noted that as landscape transformation is one of the most direct ways in which urbanization reshapes socioenvironmental relationships, it is critical to explore the spatial extent and concentration of built environments. Moreover, this aspect of the urban complex should be treated as theoretically and empirically separate from matters of population.

Taking such insights seriously, the present study shows how the relationship between the intensity of urban development and the environmental intensity of social activity hinges upon the composition of the various dimensions of urban change (e.g., the extent and concentration of the built environment, the size and density of resident populations, and the availability of social resources). More specifically, we use a random coefficients modeling approach to explore the relationships between two aspects of urban change—extent of impervious surfaces and the density of the population on such surfaces—and the carbon intensity of well-being (CIWB). As in prior research, here CIWB refers to the ratio of carbon emitted within each U.S. county to the average life expectancy within said county (Jorgenson 2014, 2015; Jorgenson and Givens 2015). In addition to analyzing the relationships between urbanization and CIWB, we explore how they may be moderated by a given county’s affluence.

Whereas some urban environmental literature is cross-national (e.g., Givens 2016, 2018; Jorgenson, Rice, and Clark 2010; Liddle 2014; McGee et al. 2015; McGee et al. 2017), the importance of large carbon dioxide (CO₂) emitters such as the United States in the success of climate change mitigation strategies—as well as the availability of relatively robust and consistent data—has led much of this research to focus on the United States (Clement, Ergas, and Greiner 2014; Clement and York 2017; Elliott and Clement 2014b; Ergas et al. 2016). The present study builds on prior research into urban landscapes and CIWB that have, as of yet, remained largely separate. By merging these analytic traditions, this study contributes to a growing body of work focused on the intersection of urbanity and carbon efficiency in the United States.

We make two principal additions to existing research. First, by interacting median household income with our two measures of urbanity—the percentage of a county’s land that is impervious surface and the population density on that impervious surface—we examine the importance of social affluence in understanding the associations that the various components of the urban complex have with socioenvironmental intensity. In examining the moderating association of income on the relationship between CIWB, population density, and impervious surfaces, we are able to explore whether cross-county inequality conditions the relationship between urban space and CIWB. Ultimately, we test whether higher-income counties have developed urban space in ways that are associated with a lower socioenvironmental intensity—as well as whether such urban forms are associated with relative increases in CIWB in lower-income areas.

Second, whereas existing research typically focuses on CO₂ emissions to explore the socioenvironmental costs and benefits of urban development, we argue that using CIWB allows for a more holistic assessment of the tradeoff between social good and environmental impact. That is to say, rather than simply exploring whether the various dimensions of urban space tend to be associated with a higher or lower rate of emissions within some political/spatial unit, we interrogate the association between urban form and the pressure that a population’s social activity tends to place on environmental systems—or the amount of CO₂ emitted per unit of life expectancy that has been gained (i.e., CIWB). National-level studies concerning CIWB most often measure it using the ratio of carbon emitted from consumption processes to average life expectancy at birth (e.g., Jorgenson 2014, 2015). However, we measure CIWB using the ratio of carbon emitted from industrial processes to life expectancy at birth. As a result, we are able to explore the relative “efficiency” of various settlement patterns in a novel way, one that directly incorporates the most significant source of greenhouse gas emissions in the United States.

**Literature Review: Environments, Well-Being, and Urban Growth**

In recent decades environmental sociologists have expanded their exploration of urbanity (Clement 2010; Foster 1999). Several substantive and theoretical works have contributed to this expanded focus on urban systems, including discussions of global urban growth, expansion of the geographic size of urban infrastructures, recognition of the porous nature of urban administrative boundaries, and the acknowledgment of the existence of a diverse array of “urban” landscape forms (Elliott and Clement 2014b; Grimm et al. 2008; Ramaswami et al. 2016). In this fashion, contemporary urban research has destabilized both the assumption of a clear urban-rural binary and the corollary assumption of a single, or typical, urban form. In doing so, such research has highlighted urbanization as a complex, multidimensional process that arises from concurrent changes in physical, demographic, and economic structures. This multidimensional approach to urbanization, in turn, has presented an opportunity to gain insight into the relative environmental efficiency of urban areas and their suburban, exurban, and rural counterparts (Clement 2010; Elliott and Clement 2014a, 2014b).

Nevertheless, research on the environmental impacts of urban growth has often yielded contradictory results (Ergas et al. 2016). On the one hand, a notable body of research argues that generally, urban growth will eventually lead to a reduction in environmental degradation (e.g., Ehrhardt-Martinez et al. 2002; Liddle 2013; Owen 2009; Satterthwaite 2010). On the other, a separate body of research has...
suggested that processes of urban growth can lead to overall increases in environmental harm at both domestic (Elliott and Clement 2014a, 2014b; Ergas et al. 2016) and international scales (McGee et al. 2015; McGee et al. 2017). Despite these contradictions (or perhaps because of them), studies of the relative environmental impacts produced by urban areas remain important to a holistic understanding of how patterns of human habitation influence local and global environmental processes.

Such a holistic understanding, however, must embrace the complexity of the relationships at issue. For instance, consider the (relatively sparse) research that has been done concerning the relationship between the various dimensions of urban development and life expectancy (the proxy measure for “well-being” in the analyses below). These studies’ findings suggest a complex, context-dependent relationship, one that is similar to the relationship between urbanization and environmental quality. For example, cross-nationally, urbanization has been found to marginally improve life expectancy at birth (Brady, Yunus, and Beckfield 2007; Kim and Kim 2016). Other cross-national research, however, has demonstrated that homicide rates, an aspect of social life that might adversely affect well-being, are positively associated with urban growth (Clement, Pino, and Blaustein 2019).

To our knowledge, work on life expectancy and urbanization in the United States is likewise fairly rare, and the research that does exist similarly suggests complexity. Research at the county level on the prevalence of hypertension, for example, has found that there is a complex and somewhat countervailing relationship between race, urbanization, regionality, and increases in mean systolic blood pressure and hypertension (Obisesan, Vargas, and Gillum 2000). The complex relationship between health outcomes and urbanization in the United States holds with respect to the expansion of impervious surfaces in particular. For instance, while the expansion of public walkways increases opportunities for walking and leisure time exercise, the expansion of roadways—and particularly the noise and traffic associated with such expansion—tends to be associated with a loss of physical capability in older adults. It should also be noted that the expansion of automobile usage and traffic congestion that accompany growth in roadways can increase asthma rates (Jackson 2002).

Although little research has been done to unpack the complex relationships between the various dimensions of well-being and urbanization, it is nevertheless clear that such relationships exist and are important. Further, as tends to be the case in developing an understanding of relationships between environmental outcomes and urban space, the multidimensionality of urbanization likely accounts for the apparently countervailing associations between well-being and the development of urban forms. Put differently, the vast array of forms that urban space may take, and the correspondingly vast array of social activity that may take place within those spaces, suggest that we should expect variation in the association between urban space and well-being, among other social outcomes. CIWB offers one way of developing a better understanding of these complexities, providing insight into how the different dimensions of urban sprawl relate to the amount of greenhouse gases emitted by a population per unit of life expectancy at birth (CIWB).

Emergent research continues to confront the multidimensionality of urban change as a means of unpacking the opposing conclusions about the carbon efficiency of urban spaces suggested by prior studies. Such work has demonstrated that urbanization processes, as well as their environmental impacts, cannot be adequately understood through an exclusive focus on administrative boundaries or categorization of populations according to size (Elliott and Clement 2014b; Ergas et al. 2016; McGee et al. 2015). Rather, metrics are needed that reflect the diversity of forms that urban spaces might take as well as the diversity of functions in which they might engage. Yet such measures must remain amenable to empirical analysis. We now turn to a discussion of such metrics.

### Literature Review: Impervious Surface Extent and Population Density

Focusing sociological examination upon constructed impervious surface—or the portion of our environments that are covered by human-made, durable materials such as concrete, asphalt, or buildings—is one way we can develop a nuanced, yet broad, understanding of urban infrastructure systems. This is especially so because impervious surface has long been understood to be an environmental indicator and potential driver of environmental processes (Arnold and Gibbons 1996; Elvidge et al. 2007; Shahtahmassebi et al. 2016; Weng 2012). Further, impervious surface provides an avenue for operationalizing many of the distinct material forms that result from the development of urban complexes. Not only do impervious surface measures help to differentiate the distinctive materialities of cities—for example, the radical material differences between Houston, Texas, and Eugene,

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1For instance, Ehrhardt-Martinez, Crenshaw, and Jenkins (2002) argue that an Environmental Kuznets Curve between urbanization and environmental impacts reflects, among other changes, a growth in service-based industries associated with urban economies. This proposition was later supported by Owen (2009), who noted that the spatial contraction of social processes that accompanies urbanization generally encourages dematerialization of economic activities within such spaces. Relatedly, Satterthwaite (2010) has argued that an important aspect of urban growth processes is the potential for an overall reduction in emissions per capita, even if total emissions continue to increase in some cities as a result of unsustainable consumption practices. We note that in the majority of such studies, it is speculated that urbanization acts to reduce the impact of human activity by moderating consumption (e.g., through affluence).
Oregon—that may be inappropriately lumped together when administrative or other designations are used (Elliott and Clement 2014b); they also allow for an assessment of similarity and difference across areas that might be colloquially characterized as urban, suburban, rural, and so forth.

Similarly, the use of impervious surface is responsive to the view, developed within urban political ecology, of the city as the product of diverse urban socionatures. In this view, “urbanization is a social process of transforming and reconfiguring nature” into new forms that are no less natural than the forms that came before (Angelo and Wachsmuth 2015:19; also see Keil 2003; Swyngedouw 1996). In this way impervious surface provides a reflection of material change as concrete is poured: a snapshot of the state of transformation. By extension, impervious surface also represents the underlying social action through which these alterations of physical form are organized and justified.

Our comparative use of impervious surface—and the density of the populations on such surfaces—at the county level also incorporates the charge of “methodological cityism” that has been levied against contemporary urban studies (Angelo 2017; Angelo and Wachsmuth 2015; Wachsmuth, Cohen, and Angelo 2016). This critique expresses concern that urban scholarship has hitherto analyzed cities as discrete units bounded by their own political borders. It argues that urban scholars have therefore ignored the ways in which urban forms are connected to political, cultural, social, and economic processes that occur across scales, and in other spaces. Correspondingly, in incorporating impervious surface at the county, and not city, level into our analysis we not only provide a means of estimating material development across wide varieties of urban life but also provide insight into the “very feature of the contemporary urban world that should make [that world] so relevant: the dimensions of the urbanization processes that exceed the confines of the traditional city” (Angelo and Wachsmuth 2015:16). Impervious surface area is a measure that likewise reflects the extent to which such change has taken place in counties that span the spectrum of relative urbanity, not only those that might typically be characterized as urban.

In addition, the durability of impervious surface expresses the accumulated, physical histories of rural areas. Finding a way to capture the diversity of physical and social histories of rural areas is essential because rural areas may have distinct socioenvironmental processes and thus different relationships to potential environmental harms (Liévanos, Greenberg, and Wishart 2018). Rural places, as well as those in between the urban and the rural, may indeed feature distinctive processes of socioenvironmental interaction and environmental inequality formation, which offer important insights into the impact of various settlement patterns on socioenvironmental outcomes of interest (Liévanos et al. 2018; Pellow 2000).

In total, impervious surfaces and the density of the population that resides on them may provide metrics that can help to reflect landscape transformation and population change across landscape categories; capture urbanization as a process, even if only momentarily or as a snapshot of a particular stage of that process; and allow for relative levels of material development to be compared across all counties in the contiguous United States (not just those classified as urban). A demographic focus on impervious surface therefore represents one method of assessing the variety of environmental contexts that exist within traditional landscape categories. To be clear, we acknowledge that like any single measure of urban space, impervious surface extent has limitations. For example, an enormous variety of processes are reproduced on impervious surface. An airport and an abandoned rural parking lot both exist on impervious surface but are clearly the foundation for very different socioenvironmental processes and relationships. It is thus important to consider the wide variety of “development” and human involvement when interpreting results. It is for this reason that we include multiple dimensions of the urban form in the present study. Specifically, by including impervious surface measurements as well as a measure of the density of population on such surfaces we are able to differentiate between not just built and unbuilt but also degrees of use and occupation of settlement formations.

For these reasons, we believe that impervious surface provides a valuable tool for studying essential components of urban development. That said, much of the form urban space takes—as well as the social and environmental outcomes associated with it—is contingent upon social contexts within which they are deployed and developed. Thus, we argue that just as urbanization and its effects cannot solely be understood as the extent of landscape constructed by humans, or as the number of bodies on such landscapes, the relative impact of urbanization cannot be fully comprehended through examining changes in the physical constitution of the space (e.g., landscape composition, population size, and population density) alone. Rather, we must consider how social and economic factors act to change the ways that the physical facets of urbanization are carried out and—as a result—how they variably benefit, or harm, both the populations within them and the environments on which they rest.

**Literature Review: Household Income, CIWB, and Industrial Pollution**

By incorporating both physical and socioeconomic aspects of urban spaces, this study seeks to extend ongoing research in environmental sociology and geography that has used the physical components of urbanization (impervious surface extent, population density, etc.) as a means of examining the nexus of landscape types and carbon emissions. Within this literature, some recent studies have focused on (1) the relationships between land use characteristics like impervious surface, carbon footprint per capita, and carbon footprint per unit of economic output (Elliott and Clement 2014b); (2) the
carbon emissions of transportation systems per unit of impervious surface population density (Ergas et al. 2016); and (3) the relative levels of household carbon emissions across urban and suburban landscape types (Jones and Kammen 2014). To date, however, no study has examined the ways in which socioeconomic factors act to moderate the associations between the intensity of urban form and environmental impact. What is more, to our knowledge no study has examined the effects of impervious surface extent, or population density, on CIWB arising from the emissions of large industrial producers across the United States. In this article we begin to address these gaps.

The concept of CIWB was originally developed to represent the ratio of anthropogenic carbon emissions to units of human well-being within a specified area or population. Using life expectancy as a proxy for well-being, CIWB has been employed primarily on a transnational basis and has tended to focus on the relationships between CIWB and metrics of economic development, such as gross domestic product (Dietz, Rosa, and York 2009, 2012; Jorgenson 2014, 2015). Meanwhile, efforts to analyze CIWB through the lens of landscape transformation, while less common than those focused on economic development, have begun to extend similar questions about relative carbon intensity of social processes into the realm of built environments (e.g., Elliott and Clement 2014b). The use of CIWB to explore the socioenvironmental impact of urban development reflects the “enduring sense that how and where humans transform local landscapes is a fundamentally sociological question” (Elliott and Clement 2014a:852; also see Clement 2010; Clement and York 2017).

Indeed, inquiry into the sociological foundations of the relationships between urban areas and their environmental consequences requires that we examine population density and human-centered metrics such as affluence in concert with the spatial and material characteristics of urbanity (Romero-Lankao et al. 2014). As Ramaswami et al. (2016:940) argue, a “larger understanding of urban infrastructure systems is necessary to move . . . ultimately, to action for urban sustainability and human well-being.” That is to say, recent research in this area strongly suggests that complete understandings of urban systems, and particularly understandings aimed at mitigating the environmental impact of settlement patterns, requires the simultaneous consideration of demographic, socioeconomic, and spatial/material components of “urban infrastructure systems.” Such “components” of settlement complexes are inherently fuzzy, largely because they are often deeply related and co-constitutive of each other. For example, we can imagine that the spatial/material dimensions of urban space (e.g., form and use of landscape) limit or facilitate the demographic (e.g., population size and population density), while socioeconomic factors (e.g., affluence as well as patterns of consumption and production) can serve to inform spatial/material conditions of settlements and are often themselves informed by the demographic features of a population.

The above example is, of course, abstract and incomplete. For our purposes it is not necessary to inventory all the ways the various components of urbanization complexes might influence and interact with each other; we simply note that they do. Further, despite the importance of the many, interrelated dimensions of urban forms’ association with socioenvironmental outcomes, how such dimensions moderate each other’s relation to environmental impact remains underexplored. To move toward a more integrative approach to understanding the relations between socioenvironmental impacts and the various dimensions of urban space, here we explore how socioeconomic factors of populations—namely, affluence—moderate the spatial/material and demographic (here captured in impervious surface extent and population density), respectively.

Recent work has demonstrated the importance of affluence to the ability of populations to mitigate emissions at the county and zip code levels in the United States (Clement, Pattison, and Habans 2017; Pattison, Habans, and Clement 2014). The findings of these works demonstrate that, as is true at the international scale (Greiner and McGee 2018; Jorgenson and Clark 2012), while there is an attenuating (“inverted U”) association between rising affluence and pollution when exploring production-based emissions, affluence tends to drive consumption-based emissions more or less continuously. Clement et al. (2017) note that these results suggest that a spatial displacement of environmentally intensive processes is occurring. The result of this displacement is that, at both the zip code level (Clement et al. 2017) and the county level (Pattison et al. 2014) (and indeed at the international level), being poor tends to be associated with greater levels of pollution, while affluence tends to be associated with environmental mitigation. As such a displacement would, by necessity, manifest itself in the various physical components of urban space (e.g., extent of impervious surfaces), we argue that interrogating the extent to which markers of physical urban change are moderated by affluence is of critical importance. Furthermore, Pattison et al. (2014) suggest that household income is an appropriate measure of affluence at the county level in this context, as it may be related to the spatial distribution of production-based emissions in ways that are distinct from overall economic output and consumption-based emissions.

It is with an eye toward the spatial displacement of industrial production processes that we construct the CIWB using production-based emissions. We focus on industrial pollution for two reasons. First, in 2016 the U.S. Environmental Protection Agency reported that approximately 50 percent of all domestic greenhouse gas emissions arose from industrial and electrical production, compared to 28 percent from transportation, 11 percent from commercial and residential emissions, and 9 percent from agriculture (U.S. Environmental Protection Agency 2018). Even bearing in mind that the assignment of responsibility for emissions may be less than crystal clear (e.g., it is debatable whether emissions arising
from electrical production should be credited against the production facility or the end user), the focus on individual, household, or consumer emissions tends to obscure the far larger contributions arising from the smaller cohort of industrial and power producers, potentially shifting blame for environmental harm away from those most responsible (Maniates 2001). By focusing on large industrial and electrical producers across the United States (using impervious surface and population density on impervious surface to represent urbanization), we directly incorporate the most significant source of greenhouse gas emissions in the country.

Second, studies of disproportionality have demonstrated an unevenness among polluters, with a few industrial “toxic outliers” producing a vast majority of pollution, even among the small cohort of industrial actors. Because disproportionate production arises from relatively few sources, the spatial consequences of pollution may likewise be uneven. This implicates environmental justice concerns over both disproportionate production as compared to the rest of the economy and disproportionately localized exposure to pollution in nonwhite and poor communities (Collins, Munoz, and JaJa 2016; Freudenburg 2005; Galli Robertson and Collins 2018). Without devaluing the contributions and importance of studies that focus on sector-specific or household carbon emissions, we seek to better understand the disproportionality suggested by (1) industry’s overall responsibility for a disproportionately large share of carbon emissions and (2) the possibility that a disproportionate share of carbon is emitted by a smaller subset of industrial actors who are not randomly distributed but likely occupy less affluent counties.

Data and Measures

Our dependent variable is CIWB. CIWB is a ratio of greenhouse gases emitted by industries within a county, measured in CO₂ equivalents, to the average life expectancy within a county. The greenhouse gas emissions data used to calculate the county-level CIWB were drawn from the U.S. Greenhouse Gas Reporting Program (GHGRP) (U.S. Environmental Protection Agency 2015) for 2011. GHGRP collects and tracks CO₂ equivalents of greenhouse gas emissions for more than 8,000 facilities across the United States from 2010 to 2018. GHGRP tracks only large emitters: those facilities that release more than 25,000 metric tons of CO₂ equivalent a year.

Data on county-level life expectancy was drawn from the University of Washington Institute for Health Metrics and Evaluation’s Global Health Data Exchange’s “U.S. County Health” data frame (Institute for Health Metrics and Evaluation 2017). The Global Health Data Exchange estimates life expectancy at birth for U.S. counties in five-year increments from 1980 through 2015. County-level life expectancy estimates used to calculate the CIWB in the present study were drawn from the 2010–2014 estimates.

Following previous research in the CIWB and environmental intensity of well-being literatures (Dietz et al. 2012; Givens 2016; Jorgenson 2014, 2015; Jorgenson and Givens 2015; McGee et al. 2017), we address dramatic disproportion in the coefficients of variation of life expectancy and emissions by adding a constant (1.384 × 10⁸) to the numerator of the CIWB equation to make the two coefficients of variation equivalent to one another. The equation for CIWB is as follows:

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CIWB = \left( \frac{CO₂ + 1.384 \times 10^8}{LE} \right) \times 100
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It is worth noting that the fact that CIWB is a ratio adds an additional layer of complexity. It is likely, for instance, that the influences that various elements of the urban form have on the industrial emission of CO₂ and the life expectancy of a population are entirely different. For this reason, we acknowledge that similar changes in the CIWB variable can be a result of more than one association between emissions and life expectancy. For example, reduction in emissions and stagnation in life expectancy would lead to a reduction in CIWB, yet so would an increase in life expectancy and stagnation in emissions. Nevertheless, we highlight that as a ratio, CIWB simply indicates the intensity at which CO₂ is emitted in order to achieve and maintain a particular life expectancy. In this sense, while the two pathways leading to reductions in CIWB are fundamentally different, each is suggestive of reductions in socioenvironmental intensity, which is what the present study is ultimately interested in understanding. Consider the physical property of density, which is also a ratio (of mass and volume). Density can be reduced by reducing mass while maintaining volume or by increasing volume and maintaining mass. Despite the fact that a single density can correspond to more than one ratio of mass and volume, developing a knowledge of density remains useful to a number of applications. Similarly, we argue that having a general understanding of the association between aspects of social life, such as urban form or economic structure, and the intensity of carbon emissions required per unit of well-being is important in understanding how social and environmental outcomes can be sustainably balanced. The spatial distribution of CIWB by county can be seen in Figure 1.

Our primary independent variables of interest are imperviousness, impervious population density, and household income. Imperviousness represents the percentage of the total county land area that consists of built, impervious structures. Data for the imperviousness variable were drawn from the 2011 National Land Cover Database (Homer et al. 2015) estimates. At the time of this research, 2011 is the most recent year of data available; thus, our analysis is limited to the single time point at which all necessary data are available (i.e. 2011). The National Land Cover Database uses satellite imaging to classify 30-square-meter parcels of land into one of 16 landcover types throughout the United States. We rely
upon a continuous, parcel-level measure of impervious surface percentage and subsequently aggregate up to the county level. In some instances, data on the levels of impervious surface were missing, so we excluded these parcels from our analysis. Using ArcGIS software, we calculated the mean impervious percentage of all 30-square-meter parcels wholly or partially within each county, and that mean was then assigned to the county. The spatial distribution of impervious surface extent at the county level can be seen in Figure 2.

The variable impervious population density is a composite measure that represents the average number of people per one square kilometer of impervious surface area at the county level. The impervious population density measure was constructed by dividing the imperviousness variable described above by the estimated population of the county. Inclusion of such a variable allows for the exploration of not just the extent of the built environment but also the number of people who are estimated to interact with and rely upon such an environment regularly. County-level population estimates were drawn from the U.S. Census Bureau’s 2010–2014 American Community Survey five-year estimates and were provided by the National Historic Geographic Information System (Minnesota Population Center 2011). The spatial distribution of impervious population density can be seen in

Figure 1. Carbon intensity of well-being calculated at the county level as a ratio of industrial emissions of carbon dioxide equivalents (emitters that release >25,000 metric tons annually) for each county divided by its life expectancy at birth.

Figure 2. Percentage of impervious surface estimated at the county level as the mean impervious surface percentage for all 30-square-meter 2011 National Land Cover Database grid squares wholly or partially within that county.
In addition to the primary independent variables of interest described above, we include several demographic and geographic controls. Using a hierarchical linear modeling approach, we control for state-specific factors, such as the leading political party, and unique laws and regulations that might be in place, such as urban growth boundaries.\(^2\) The variable total land area is included to account for the fairly wide variation in land area of U.S. counties across the contiguous United States as well as to provide a proxy for regional variation in county land area. To account for drivers of CIWB related to the size of populations outside of impervious spaces, we include the control variable total population. Thus, the associations identified below are found to exist net of total land area and total population in a county. As a large body of literature has noted that there is a strong relationship between racial minority presence and the presence of industrial processes and pollutants (for a review, see Mohai, Pellow, and Roberts 2009), we control for the percentage of the population that identifies as white. Finally, we control for the percentage of the population in the county with no high school degree to account for differences in less tangible resources that might be mobilized to keep pollution down relative to life expectancy, and which are associated with education level.

Descriptive statistics of the variables included in the analyses, presented in their raw (i.e., exponentiated) form, are displayed in Table 1.

Figure 3. Median household income was also drawn from the 2010–2014 American Community Survey and represents the median household income of the county.

In alternate analyses we included controls for U.S. Environmental Protection Agency region. Such models did not change the results in any significant way and are not presented here as a result.
Hypotheses

In light of the literatures discussed above, we put forth four hypotheses.

Hypothesis 1: Imperviousness will be associated with increases in CIWB across counties.  
Hypothesis 2: Median household income will serve to decrease the effect of imperviousness on CIWB, indicating that spatial displacement of production processes leads to a more beneficial association between physical components of urbanization and CIWB in more affluent areas.  
Hypothesis 3: Impervious population density will be associated with increases in CIWB across counties.  
Hypothesis 4: Median household income will serve to decrease the effect of impervious population density on CIWB, indicating that spatial displacement of production processes leads to a more beneficial association between demographic components of urbanization and CIWB in more affluent areas.

Analytic Strategy

To explore the relationship between CIWB and imperviousness, CIWB and population density, and how median household income moderates such relationships, we employ a hierarchical linear modeling approach. Using a hierarchical linear modeling approach has the benefit of allowing for counties to be clustered by U.S. state, which serves to account for correlation of county-level observations within states, thereby reducing bias in estimates of standard errors. Thus, utilizing a hierarchical linear modeling approach allows for control of the political climate, state-based regulations, and difficult-to-measure geographic factors. Finally, we note that hierarchical linear modeling “shrinks” or weights estimates from groups with few individuals in toward the global estimate, ultimately reducing potential bias introduced from unique groups on final estimates (Evans et al. 2018; Greiner and McGee 2018; Xu 2014). Such weighting is not inconsequential, as there is a rather wide variation in the number of counties within states.

Results

Results of all analyses are presented in Table 2. The estimated moderating association of median household income on the relationship between imperviousness, impervious population density, and CIWB can be found in Table 3. Graphic depictions of the moderating association of median household income on the relationship between imperviousness and CIWB, as well as impervious population density and CIWB can be found in Figure 4 and Figure 5, respectively.

Impervious Surface

Model 1 of Table 2 indicates that a 1 percent increase in the extent of impervious surfaces across counties is associated with a small, but statistically significant, increase in CIWB, offering support for hypothesis 1. Model 1 also suggests that counties where the percentage of the population that identifies as white, as well as where the median household income is higher, have relatively lower CIWB.

In model 2 of Table 2 an interaction between imperviousness and median household income is included. We find that the interaction effect is negative and statistically significant at an \( \alpha = .05 \) two-tailed test, which lends support to hypothesis 2. The incorporation of the interaction term changes the meaning of the reported main effects of imperviousness and median household income substantially. To aid in the interpretation of...
the interaction effect presented in model 2, we turn to Table 3 and Figure 4. Examination of the estimated coefficients presented in Table 3 indicates that despite the negative interaction effect between imperviousness and median household income, it is only at rather high levels of income that impervious surface extent is associated with reduced CIWB. In fact, close examination of estimated coefficients reveals that the association between imperviousness and CIWB is never both negative and statistically significant at an \( \alpha = .05 \) two-tailed test. When a county’s median income is roughly $59,042, the association of impervious surface area extent with CIWB is reduced to .004, but beyond that value of median household income, imperviousness is no longer found to be statistically significant. This suggests that hypothesis 2 is at least partially

| Variable                          | Model 1         | Model 2         | Model 3       | Model 4        |
|-----------------------------------|-----------------|-----------------|---------------|---------------|
| Imperviousness                    | .007***         | .121***         |               |               |
|                                   | (.002)          | (.028)          |               |               |
| Impervious population density     | —               | —               | -.007***      | .192***       |
|                                   | (.002)          | (.028)          | (.002)        | (.047)        |
| Total land area                   | .007***         | .007***         | .000          | .000          |
|                                   | (.002)          | (.002)          | (.001)        | (.001)        |
| Total population                  | .000            | .000            | .006***       | .007***       |
|                                   | (.001)          | (.001)          | (.000)        | (.000)        |
| Median income                     | -.035***        | -.027***        | -.035***      | .110***       |
|                                   | (.005)          | (.005)          | (.005)        | (.034)        |
| Percentage white                  | -.027***        | -.031***        | -.027***      | -.029***      |
|                                   | (.004)          | (.004)          | (.004)        | (.004)        |
| Percentage with no degree         | .019***         | .019***         | .019***       | .019***       |
|                                   | (.003)          | (.003)          | (.003)        | (.003)        |
| Income \times Impervous           | —               | -.011***        |               |               |
|                                   | (.003)          | (0.003)         |               |               |
| Income \times Density             | —               | —               |               | -.019***      |
|                                   | (.004)          |               |               | (.004)        |
| Constant                          | 19.293          | 19.223          | 19.425        | 17.880        |
| Counties/States                   | 1.883/49        | 1.883/49        | 1.883/49      | 1.883/49      |
| Log likelihood                    | 3.840           | 3.849           | 3.840         | 3.849         |

Note: All variables are natural log transformed. Coefficients represent the percentage change in carbon intensity of well-being associated with a one-unit change in the dependent variable. Standard errors are in parentheses. Dashes represent instances wherein the variable in question was not included in the model. Coefficient *** \( p < .001 \).

| Median Income Value | Estimated Impervious Surface Coefficient | Estimated Population Density Coefficient |
|--------------------|------------------------------------------|----------------------------------------|
| 1st percentile     | .016***                                  | .018***                                |
| ($19,146)          | (.003)                                   | (.004)                                 |
| 25th percentile    | .009***                                  | .006***                                |
| ($38,583)          | (.002)                                   | (.002)                                 |
| Median             | .007***                                  | .004***                                |
| ($44,709)          | (.002)                                   | (.001)                                 |
| 75th percentile    | .005*                                    | .002                                   |
| ($51,597)          | (.002)                                   | (.001)                                 |
| 99th percentile    | -.004                                    | -.013***                               |
| ($123,966)         | (.003)                                   | (.004)                                 |

Note: All variables are natural log transformed. Coefficients represent the percentage change in carbon intensity of well-being associated with a one-unit change in the independent variable. Standard errors are in parentheses. Coefficient * \( p < .05 \), ** \( p < .01 \), *** \( p < .001 \).
incorrect. There appears to be no circumstance in which affluence results in a negative relationship between CIWB and imperviousness. Note that this does not suggest that affluence is not an important aspect of the association that imperviousness has with CIWB. As can be seen in Figure 4, the relationship of impervious surface area extent with CIWB is substantially lower in wealthier counties than it is in low-income counties. Ultimately, we suggest that the impact that impervious surface area extent has on the environmental intensity of social processes is largely dependent on the...
financial resources of the community in question. Specifically, the more affluent a community, the more effectively it is able distance itself from environmentally intensive uses of built environments. Such a finding supports the claims made in previous work (Clement et al. 2017; Pattison et al. 2014) that affluent localities are able to reduce production-based emissions by spatially displacing them to poor, or relatively less affluent, counties. While it appears that growth in imperviousness across counties tends to relate to higher levels of environmental intensity, counties that have higher income levels are able to mitigate the negative effects of such expansion to a notable degree—even while others are not.

**Impervious Population Density**

In model 3 we investigate the relationship between impervious population density and CIWB. Findings suggest that while the extent of imperviousness decreases the effectiveness with which production-based emissions are able to yield increases in social well-being, increases in impervious population density across counties is associated with reductions in CIWB. Taken together, these findings suggest that having a greater level of built environment negatively affects socioenvironmental relations, but concentrating populations into such environments generally leads to improvements in such dynamics—indicating that hypothesis 3 is incorrect. In addition, we note that as in model 1 and model 2, increases in both percentage white and median household income are associated with reductions in CIWB.

In model 4 we replicate the logic applied in model 2 and explore the moderating relation that median household income has with the association between impervious population density and CIWB. In model 4 we see that incorporating the interaction effect renders the main effect of impervious population density on CIWB positive. Model 4 also demonstrates that a negative interaction between impervious population density and median household income exists, lending support to both hypothesis 3 and hypothesis 4. Turning to Table 3, we see that while the association of impervious population density with CIWB decreases as the household income of counties increases, it is only in the wealthiest counties that the association between impervious population density and CIWB becomes both negative and statistically significant. Specifically, the association of population density becomes negative and significant in counties with median incomes of about $77,420. These relationships are shown graphically in Figure 5, where it can be seen that in wealthier counties, the relationship between CIWB and impervious population density is decoupled and that in the very wealthiest counties the trajectory of the relationship is actually reversed. These findings clearly support hypothesis 4 and suggest, once again, that the relationships between the constituent dimensions of urban space and CIWB are largely dependent on the availability of economic resources within the county being discussed. More specifically, we find that in relatively affluent counties, having a higher population density on impervious surfaces is associated with lower CIWB, thereby indicating that such spaces typically enjoy an improved CIWB. Conversely, we should expect that in counties with lower median household income, growing the population density of built environments will increase CIWB, indicating a reduction in the gain in life expectancy per unit increase in emissions.

**Discussion**

In this article we add to the growing body of research that seeks to address and explain a central question in studies of urban space: whether the increasing intensity of urbanization is associated with better or worse socioenvironmental outcomes. To do so we use a hierarchical linear modeling approach in which U.S. counties were clustered within states to understand the relationships between (1) county-level demographic and landscape features and (2) CIWB. Given our goal of understanding the environmental consequences of urban forms in varying socioeconomic contexts, we interact a measure of the intensity of local built environments (impervious surface) and a measure of the intensity of reliance of human populations on those environments (impervious surface population density) with household median income to assess the dynamism of their associations with CIWB across counties. This approach allows us to develop a more flexible understanding of the socioenvironmental meaning these dimensions of urban space have for each county. We highlight that use of the interaction enables an understanding of the socioenvironmental outcomes of these important aspects of urban development not in isolation but in combination.

By using CIWB, or the ratio of carbon emitted from industrial processes to the average life expectancy within a county, we were able to more effectively explore the relative “environmental efficiency” of various settlement patterns. Put differently, using the CIWB measure allowed us to explore the relationship between the extent of impervious surfaces within a county and the social benefit that is yielded per unit of CO₂ emitted. Similarly, use of CIWB enabled an exploration of the association between the density of the population that resides on impervious surfaces and the social benefit that is yielded per unit of CO₂ emitted. Further, by interacting household income with these two measures of urban development, we facilitate an exploration of the role that affluence plays in the relationship between urban form and socioenvironmental impact. The use of such an interaction allows, in a cursory manner, for an exploration of the role that cross-county inequality plays in the relationship between establishment of an urban complex and CIWB.

We find that imperviousness, total land area, and percentage with no high school degree are positively and significantly related to industrial CIWB, while percentage white and median household income are significant and negatively associated with it. The addition of an interaction between
imperviousness and median income revealed that the socioenvironmental impact of built environment is less in more affluent areas. In models where impervious population density was the primary independent variable of interest, we similarly found that impervious population density, median household income, and percentage white had significant, negative associations with industrial CIWB. In turn, percentage with no high school degree had a significant positive association with industrial CIWB. Adding an interaction between impervious population density and household median income demonstrated that with the exception of relatively affluent counties, counties with a higher population on one square kilometer of impervious surface tend to have higher CIWB.

We draw attention to the finding of a positive, significant association between imperviousness and CIWB (i.e., increased carbon intensity) at lower income levels and highlight that the magnitude of this relationship is attenuated as median household income increases. Income has a similar, albeit more exaggerated, influence with respect to impervious population density. In this case, CIWB is positively associated with impervious population density in counties with lower income levels, yet by the 75th percentile of median household income, the association is reversed—the impact of population density becomes increasingly negative as income grows.

These findings suggest that on average, increases in household income can serve to attenuate the relationship between growth in the physical and demographic components of urbanization and CIWB. Such findings indicate that considerations of cross-county inequality may be important when attempting to weigh the socioenvironmental costs and benefits of favoring one settlement pattern over others. In this respect, our findings draw attention to the ways that environmental privilege develops from the processes of deindustrialization and the establishment of service economies that high levels of affluence seem to afford. Nevertheless, our findings do not suggest that emissions related to these more privileged settlement forms have disappeared completely. Rather, the locus of industrial emissions has likely shifted to less affluent urban and rural areas and is therefore tied to lower levels of affluence.

Considering this, we suggest that future work should take seriously the growing literature on methodological cityism and grapple with the fact that the locus of industrial emissions in an urban area may, or may not, be confined within urban political boundaries. Correspondingly, while our findings support the idea that affluence tends to moderate local CIWB, they also demonstrate that the presence of intercounty environmental privilege has developed from the interaction of the built environment, the relationship between population density and the built environment, and relative affluence. Thus, we highlight that measures of environmental privilege based on any single component of urban development—whether that be impervious surface or the intensity with which such areas are occupied—may miss important aspects of the diversity of socionatures human settlements represent as well as how it is these socionatures correspond to varying socioenvironmental outcomes.

Based on the findings presented above, we suggest that each of the two sides to the debate about the relative environmental intensity of cities, at least in the context of industrial emissions on a U.S. county scale, is potentially “correct.” Which side is correct, however, depends to a significant degree on the socioeconomic profile of the county under consideration. On the one hand, imperviousness and population density of imperviousness are both associated with greater carbon emissions per unit of life expectancy in the vast majority of county income contexts. On the other, in the most affluent counties this relationship attenuates and eventually reverses. Therefore, in a majority of contexts greater urbanization may be viewed as having worse environmental consequences, but at higher levels of affluence urbanity may lead to more desirable socioenvironmental outcomes.

**Conclusion**

The socioenvironmental impacts of social settlement strategies are key conditions of understanding the merit of climate mitigation and adaptation strategies. The diverse literature that explores settlement patterns, however, often provides contradictory results that may translate to contradictory or confusing advice for planners. To better elucidate the relationships between some of the factors that may drive these contradictions, in this article we explore the relationship between two aspects of urban change—extent of impervious surfaces and the density of the population on such surfaces—and CIWB at the county level of the United States. We also explore how the associations between these components of urban social life are moderated by county-level affluence.

We focus on the most important sectoral source of carbon emissions in the United States, industrial pollution, as well as on the concurrent and co-constructed impacts of landscape, demographics, and affluence. Our findings suggest that more built counties tend to have greater CIWB. However, we also find that exceptionally affluent counties may, as a possible result of deindustrialization and political NIMBYism, emit less carbon per unit of life expectancy than others. Such findings provide evidence that cross-county income inequality may be a critical and underexplored feature of the relationship between urbanity and environmental consequences.

In another sense, however, our findings are somewhat surprising and add to the literature on carbon intensity in a unique way. In particular, our observation that affluence interacts with landscape to influence CIWB encourages a view of socioenvironmental variables as developing not in isolation but in combination. Such an observation suggests that the fundamentally sociological processes of landscape transformation (Elliott and Clement 2014a) are related to
more traditional considerations of environmental sociology, like socioeconomic status, in interesting and heretofore unexplored ways. Taking a fine-grained approach that builds off of a number of literatures, our analysis indicates that while landscapes matter, the ways that landscapes are populated and the conditions that characterize those populations also matter. However, we also note that our ability to generalize these findings, and to contribute to the understanding of urban development as a multidimensional process of social change, is limited by our use of a cross-sectional analysis. To that end, we hope that future research will expand upon what has been done here as more data become available.

Finally, we note that a full discussion of the consequences of our findings with respect to environmental justice is outside of the scope of this article. However, we believe that potential exists for a rich cross-pollination between environmental justice traditions and the interrogation of the co-constituted socioenvironmental outcomes of landscape development, demographic factors, and the broader array of features that constitute urban systems both within and beyond the technical borders of cities. We hope that future research will continue to address these relationships with the goal of ensuring more just outcomes across spaces and patterns of human habitation.

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