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- Urban socio-institutional dynamics are important influences on energy use and GHG emissions
- No consensus exists on details of urban socio-institutional-GHG relationships
- Integrated research for an urbanization science is necessary

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Urbanization and the carbon cycle: Contributions from social science

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Abstract This paper outlines the contributions of social science to the study of interactions between urbanization patterns and processes and the carbon cycle, and identifies gaps in knowledge and priority areas for future social scientific research contributions. While previously studied as a unidimensional process, we conceptualize urbanization as a multidimensional, social and biophysical process driven by continuous changes across space and time in various subsystems including biophysical, built environment, and socio-institutional (e.g., economic, political, demographic, behavioral, and sociological). We review research trends and findings focused on the socio-institutional subsystem of the urbanization process, and particularly the dynamics, relationships, and predictions relevant to energy use and greenhouse gas emissions. Our findings suggest that a multidimensional perspective of urbanization facilitates a wider spectrum of research relevant to carbon cycle dynamics, even within the socio-institutional subsystem. However, there is little consensus around the details and mechanisms underlying the relationship between urban socio-institutional subsystems and the carbon cycle. We argue that progress in understanding the relationship between urbanization and the carbon cycle may be achieved if social scientists work collaboratively with each other as well as with scientists from other disciplines. From this review, we identify research priorities where collaborative social scientific efforts are necessary in conjunction with other disciplinary approaches to generate a more complete understanding of urbanization as a process and its relationship to the carbon cycle.

1. Introduction

The study of contemporary urbanization and its impact on the environment is increasingly central to a wide variety of scientific disciplines. Increasing attention is due to the rapid growth of cities in many parts of the world, the growing awareness of the importance of society-wide social, biophysical, and infrastructural changes that accompany urbanization, and how these dramatic shifts influence trends across a range of environmental issues at multiple geospatial and temporal scales [*Douglas*, 2013]. Of particular concern is the role of cities and the urbanization process in climate change and specifically the carbon cycle [*Seto et al.*, 2014].

Social scientists have long studied urbanization and are increasingly addressing urban impacts on climate. Major questions explored by research in this area that are relevant to the carbon cycle include: (1) what explains the patterns and dynamics of urbanization? and (2) how and why does urban growth and urbanization affect energy use and greenhouse gas emissions? The ways in which social scientists answer these questions are as varied as the disciplinary perspectives of political science, anthropology, demography, economics, geography, psychology, and sociology, among other fields.

For this review, we focus on social science contributions to urbanization and climate change. That is, we review the aspects of urbanization that are defined by human activity, human interactions, and the nonmaterial constraints (norms, values, rules, and regulations) placed upon these dynamics. Together these activities, interactions and constraints make up the socio-institutional subsystem of urbanization (see below, section 2). An important underlying assumption is that the features and dynamics of concern to social scientists are major components and determinants of urbanization processes and directly and indirectly influence the carbon cycle. The goal of the review is to determine the extent to which various aspects of the socio-institutional subsystem structure the relationship between urbanization and the carbon cycle and the ways in which these dynamics can be (or have been) altered to minimize negative environmental effects.

In the backdrop of our study are ongoing debates about whether urban growth and urbanization are fundamentally detrimental to environmental quality [*Srinivas*, 2000; *Brown*, 2001] and in this case contribute to climate change or, with appropriate governance, incentives, and cultural capacities [cf. *Satterthwaite*, 2007], urbanization can be a potential path toward low carbon societies [*Owen*, 2009; *Glaeser*, 2011]. Empirical research has been limited by difficulty in teasing out the singular environmental impact of urbanization from other developmental processes making it difficult to support either scenario. This review suggests that the features of socio-institutional systems that help to structure the relationship between urbanization and the carbon cycle are far from well enough understood to determine whether and how the effects of urbanization on the carbon cycle can be best reduced. As will be demonstrated in the following sections, the social science studies of urbanization have only recently integrated energy use and subsequent greenhouse gas (GHG) emissions as important outcomes of patterns of growth and social dynamics. [In this paper, we use carbon and GHG emissions interchangeably. We understand that different studies have examined different compounds (CO_2, CH_4, N_2O, HFCs, PFCs, etc.), but that most if not all discuss results in terms of carbon, CO_2 equivalents, or GHGs.] Much work on socio-institutional systems occurs within disciplinary boundaries and lacks integration with other social science fields notwithstanding the natural and physical sciences. Moreover, studies examining the relationship between socio-institutional systems and energy use and GHG emissions have produced consensus at only the broadest levels (e.g., urban wealth and urban energy use are correlated) and debate continues around the directionality and mechanisms underlying many such relationships. Importantly, the literature discusses urbanization, but often focuses on cities and city growth. When urbanization is the focus of research, the process is represented as unidimensional, typically as the share of population living in cities. We argue that given the current global environmental trends, these gaps need immediate attention from the social scientific community.

The review first briefly describes the limitations of contemporary definitions of urbanization and provides a more inclusive and integrated framework for understanding the process. The next section reviews and describes the variety of social science contributions to understanding the urbanization process. While these studies have not focused exclusively on the effects of urbanization on the carbon cycle, they provide insight into possible routes of influence. The following section synthesizes social science research that specifically examines how different features of the socio-institutional subsystem affect urban energy use and GHG emissions. In the final section, we conclude by providing a series of priorities to help overcome current research gaps and challenges.

2. What Is Urbanization?

Urbanization is a powerful process, shaping the way people interact with each other and their environment. Traditionally, social science scholars identify urbanization as the territorial shift of population from dispersed rural areas to more concentrated urban areas [*Tisdale*, 1942; *Berry*, 1973]. The United Nations' World Urbanization Prospects (WUP) defines the urbanization rate as the proportion of the population living in urban areas [*United Nations*, 2012]. Both methodological and conceptual criticisms associated with this unidimensional definition have arisen. Methodologically, boundaries of "urban" areas change over time making it difficult to keep up with the proper delineation of these spaces. Despite the popularity of the WUP indicators, they have been routinely criticized because the methodology relies on local- and country-specific definitions of bounding urban areas, resulting in often incomparable and widely divergent definitions of the population, density thresholds, or administrative/political units designated [*Satterthwaite*, 2007]. Various scholars have proposed alternative globally standardized methods to delineate urban boundaries [*Schneider et al.*, 2009], although little consensus exists as to how best to define and delineate urban entities for empirical examination.

These methodological differences create challenges for estimating urban GHG emissions. Distinguishing between different types of urbanized areas (core, suburb, and periphery among small, medium, large, metropolitan, and mega-urban regions) is important to estimate carbon emissions [*Steinberger and Weisz*, 2013]. Variation among researcher's identification of urban boundaries and how these areas change over time makes it difficult to discern spatially and temporally consistent emission trends and drivers [*Parshall et al.*, 2010]. For example, in the developed world, *Jones and Kammen* [2014] highlight important differences between urban core, suburban, and metropolitan consumption-based, zip code level carbon footprints. *Minx et al*. [2013] find similar results for the UK. The spatial distribution of urban GHG emissions, between core and periurban areas, however, differs dramatically from these trends in the developing world [*Marcotullio et al.*, 2013b].

Conceptually, many social scientists argue that urbanization is as much a social process related to shifting relationships and the emergence of unique qualities and properties of socio-institutional systems as it is the identification of specific spatial entities and quantification of their growth [*Wirth*, 1938]. Given these weaknesses some have argued that the contemporary definition of urbanization varies across disciplines and invariably represents different entities while failing to capture important processes [*McIntrye et al.*, 2000], which can significantly affect the identification of policies for sustainable development [*Marcotullio and Solecki*, 2013].

The lack of consensus as to a representative and inclusive definition of urbanization has encouraged us to seek new ways to define and understand the process. We recognize that demographic shifts alone, or definitions based upon delineated boundaries alone, do not adequately describe the changes in the way urbanizing societies and economies organize [*Knox and McCarthy*, 2005] nor the built environment and biophysical characteristics of urbanization. Those involved in a 2013 Workshop on Human-Carbon Interactions in the Urban System, sponsored by the Carbon Cycle Interagency Working Group (CCIWG) and the US Carbon Cycle Science program, propose urbanization as a multidimensional process that arises from changes in societies' socio-institutional [*Montgomery et al.*, 2003], technological (as it pertains to changes in the built form) [*Berry et al.*, 1970; *Tarr*, 1988], and natural environment [*Hough*, 1984; *Spirn*, 1984; *Grimm et al.*, 2008] subsystems differentially across space and over time (for a more detailed description, see Figure 1 in *Romero-Lankao et al.* [2014]). We argue that viewing urbanization in this multidimensional way allows for a broader and more inclusive understanding of important processes that affect the carbon cycle.

3. What Explains Historic and Regional Patterns and Dynamics of Urbanization?

Social scientists have been exploring the urbanization process for over 100 years [*Weber*, 1899] from a wide variety of perspectives. While it is not possible to review all perspectives, we describe the major currents in the study of historic and regional processes of urbanization.

The dominant descriptive theory of urbanization is provided by demographers, who largely examine the geographic shift in population from sparsely settled to dense human settlements and examine transitions in birth and death rates, population age structure, family size and structure, and gender balance accompanying these shifts [*Thompson*, 1929; *Zelinsky*, 1972]. Contemporary thinking links urbanization to the demographic transition of societies from high birth and death rates to low birth and death rates [*Montgomery*, 2008] and by the movement of people to high concentration areas that provide economic wealth and access to health care. Moreover, in societies with high proportions of population living in urban areas, demographers suggest that the relative advantages and disadvantages of urban life drive "cycles of urbanization," or spatial and temporal fluxes in concentration, de-concentration, suburbanization, and re-urbanization of populations [for a review, see *Champion*, 2001]. Hence, demographers base an understanding of urbanization patterns on the movement of populations to dense settlements and the demographic changes that accompany this transition.

Economists explain the movement of people to cities as being a consequence of "push" and "pull" factors [*Todaro*, 1997]. They argue that changes in a societies' economic structure, advances in technologies, and differential levels of productivity among sectors that accompany economic growth [*Davis and Henderson*, 2003] help to push people away from rural areas and pull people to live in cities [*Bradshaw and Fraser*, 1989; *Annez and Buckley*, 2009]. Advantages brought about by these population shifts include better and faster communications and transport, increases in returns to scale, agglomeration economies, and further advances in technology, all of which bring substantial benefits for industry, generate economic activity, and increase wealth [*Anas et al.*, 1998; *Glaeser*, 1998; *Quigley*, 1998; *Montgomery et al.*, 2003]. Moreover, higher urban population density increases productivity [*Ciccone and Hall*, 1996]. These dynamics drive further economic activity, which in turn drives more intense "push" and "pull" signals [*Williamson*, 1965; *Annez and Buckley*, 2009]. On the other hand, economists recognize that firms and individuals also respond to congestion, noise, stress, crime, disease, and pollution, which can increase costs and reduce the attractiveness of cities. In contemporary, mature economies, economists suggest that urbanization continues, but with an emphasis on the type of economic activities, such as the increase in service provision, and the way cities economically link to each other [*Taylor*, 2004]. Hence, economists base an understanding of urbanization patterns on the outcomes of tensions that firms and individuals experience between the economic attractiveness of concentration versus dispersal. Those societies that provide more economically attractive urban centers experience more rapid urbanization than those that do not.

Other social scientists have also sought to place urbanization patterns in a larger context that includes the forces of modernization, industrialization, and capitalist development. Many sociologists find the concentration of people in cities to be puzzling, given the erosion of traditional norms and kinship bonds that often accompany urbanization [*Park et al.*, 1927; *Wirth*, 1938]. This puzzle was partially addressed by conceptualizing the urbanization process as similar to biotic succession [*Park et al.*, 1927]. That is, these early urban sociologists posit economic "laws" as defining the emergence of "natural areas" that underpin the expansion of cities, much like natural selection defines the course of evolution. The spatial implications of this thinking are manifest in the "concentric ring model" of urban expansion and its variants [*Harris and Ullman*, 1945].

A wide range of contextual factors may explain the variation and dynamics of urbanization patterns. Some view cities as the storehouses of culture and creativity, and propose that urbanization is a consequence of the attractiveness of these social benefits [*Mumford*, 1961]. Other social theorists, however, see urbanization as part of larger structural forces operating at a national, if not international, level such as the uneven spatial distribution of wealth and economic growth [*Harvey*, 1973; *Castells*, 1977; *Lefebvre*, [1970] 2003]. *Harvey* [1989], for example, argues that investment in land and real estate is critical to accumulating wealth and capital, which in turn promotes urban growth as an increasingly more efficient arena for profit making. The demand for such growth is met by national, state, and local policy-making for development and land use [*Jessop*, 1990]. In this conception, urbanization is the consequence of governmental and private actors operating at a variety of scales collectively mobilizing resources [*Friedmann and Wolff*, 1982]. Cities and urbanization therefore are viewed as the manifestation of capital accumulation processes at multiple scales [*Lo and Yeung*, 1998; *Sassen*, 2006]. In each case, however, urbanization is a result of other social and economic forces and would not exist were it not for these influences.

The political influence of powerful elites and the growing complexity of governing institutions [*Weber*, 1966] have also been found to shape urbanization patterns. For example, scholars point to the importance of colonial powers in creating the core metropolises in developing countries [*Vance*, 1970], which have impacted the subsequent distribution and organization of national urban growth [see, e.g., *Gilbert and Gugler*, 1992]. Cities in the developing world are growing more rapidly than those of the developed world a century ago [*de Sherbinin and Martine*, 2007; *World Bank*, 2009], and often without the rise in income that accompanied previous urbanization. This "over urbanization," or urbanization without industrialization and the growth of primate cities, creates national city-systems that are arguably structurally locked into low economic and social development trajectories [*Hoselitz*, 1955; *Timberlake*, 1985]. One important factor in creating this pattern of urbanization is an "urban bias" [*Lipton*, 1977] created in emerging and poor economies, as cities are centers for elite communities and therefore command a disproportionate share of a nation's fiscal and social resources [for a review, see *Jones and Corbridge*, 2005]. In the developed world, urban politics has been conceptualized as dominated by regimes or authoritative coalitions in urban areas able to drive urbanization patterns [*Logan and Molotch*, 1987; *Stoker*, 1998; *Stone*, 1989]. From this perspective urbanization is the outcome of the priorities and influence of elites that are able to direct resources toward specific goals.

This brief overview suggests that a variety of perspectives on urbanization have important contributions to our understanding of social and institutional dynamics. Our intent is to promote an integration of these perspectives within the social sciences and with those of the biophysical sciences. This integration is critical as the different dynamics described above also influence the flows of carbon through and GHG emissions from urban areas and from societies at different stages in the urbanization process. Without a holistic perspective, the determinants of energy use and GHG emissions—and resulting opportunities for their control—may be missed or misunderstood. In the next section, we review some of the ways in which social science scholars have identified these influences.

4. How and Why Does Urbanization Affect the Carbon Cycle?

Urbanization affects the carbon cycle indirectly and directly by facilitating release and absorption of carbon [for details, see *Chester et al.*, 2014; *Hutyra et al.*, 2014]. For example, urbanization brings higher energy consumption and increased burning of fossil fuels from industrialization, the mechanization of agriculture, and the transportation of food to cities [*Jones*, 1991]. As cities grow, the concentration of population and concomitant changes in social, political, behavioral, and economic activities accelerate carbon releases through land use change, and increased use and consumption of energy and materials. Alternatively, urban vegetation can absorb carbon from the atmosphere and cities can temporarily store carbon in building materials and other infrastructure [*Pataki et al.*, 2006]. Although direct carbon sequestration by urban plants and soils is negligible as compared with urban GHG emissions, local cooling effects that reduce energy use can be substantial [*Pataki et al.*, 2011].

It is important to note that social scientific work on urbanization's influence on the carbon cycle is typically based upon published urban GHG emission estimates. These estimates are diverse due to the absence of a commonly accepted protocol, lack of data, and choices made in compilation and analyses of data [*Seto et al.*, 2014]. Reviews of this literature concede difficulty in making direct comparisons of emission levels across different sets of analysis [*Bader and Bleischwitz*, 2009; *Kennedy et al.*, 2009; *Ramaswami et al.*, 2012]. In this issue, *Chester et al.* [2014] and *Hutyra et al.* [2014] overview GHG emission methods for total urban, engineered, and urban natural systems. We return to this problem later in the paper when reviewing research needs.

In this section, we focus on the multiple factors proposed by social scientists to explain the extent to which urbanization contributes to the release of carbon through energy use and subsequent GHG emissions. There are several findings from this review. First, while there is a rich and growing literature on the relationship between urban socio-institutional systems and the carbon cycle, most research typically is focused on urbanization as a state, or cities as entities, rather than on urbanization as a process of change. Second, the socio-institutional studies of urbanization and the carbon cycle frequently examine one or a few causal factors, but in many cases the effects of socio-institutional factors on urban energy use and GHG emissions can be multiplicative and interactive. Finally, results suggest that there is agreement at only the broadest levels (e.g., energy consumption is influenced by urbanization), but directionality and causal mechanisms are poorly understood.

In the following subsections, we review the ways in which the qualities of urban populations, the economic shifts that accompany urbanization, behavioral change, and the policy and politics of urban growth determine the implications of current and future energy use and carbon emissions.

4.1. Urban Demographic Characteristics Influence Energy Demand and GHG Emissions

As demonstrated from studies of cities, larger population size is unambiguously associated with higher aggregate urban energy demand and associated GHG emissions [*Hoornweg et al.*, 2011; *Marcotullio et al.*, 2013b; *Jones and Kammen*, 2014]. This is theoretically the cumulative result of concentrated people and economic activity, which requires more energy-intensive processes in agriculture, transportation, buildings, industry, and waste management [*Liddle*, 2014]. Despite consensus about the positive effect of population size on energy demand, social science scholars debate the magnitude of the effect and the implications of future urbanization for energy demand and GHG emissions. Some scholars suggest that the effect of population size on energy or carbon demand is contingent on the interaction between population size and other factors. For example, the effect of population size on energy demand may depend on a city's starting population size [*Bettencourt et al.*, 2007]. Some evidence for this scaling relationship suggests that urban areas with larger population sizes have proportionally smaller energy infrastructures than smaller cities [*Bettencourt et al.*, 2007; *Fragkias et al.*, 2013]. Other evidence suggests that GHG emissions may increase more than proportionally to population size, such that larger cities exhibit proportionally higher energy demand as they grow than do smaller cities [*Marcotullio et al.*, 2013b]. Theoretically, this may be possible due to diminishing returns, threshold effects, negative synergisms, and the disproportionate escalation of cost for maintaining environmental quality with population growth [*Ehrlich and Holdren*, 1971].

The effect of population size of cities on energy demand and GHG emissions is dependent on the concomitant population density. For instance, theoretically, dense settlement affords energy efficiencies by encouraging multidwelling living, public transit use, walking and cycling, and reducing winter energy demand in buildings due to urban heat island effects [for a review, see *Oleson et al.*, 2008; *Boyko and Cooper*, 2011]. The studies of *Newman and Kenworthy* [1989, 1999] demonstrate a negative relationship between population density and transportation fuel use. These results are supported by more recent research on transportation energy consumption [*Liddle*, 2014], electricity consumption in buildings [*Lariviere and Lafrance*, 1999], and overall urban GHG emissions [*Marcotullio et al.*, 2013b]. Despite these general results, however, scholars have found the urban population density-GHG emission relationship far from straightforward. Some scholars have argued that the correlation between density and congestion is positive and dense populations where workers and consumers need to travel long distances may subsequently use more energy [cf. *Gordon and Richardson*, 1998]. Empirical research suggests that density is only one of several factors influencing travel in compact settlements [*Ewing and Cervero*, 2001; *Transportation Research Board*, 2009]. Recent work reviewing the large literature on the relationship between vehicle miles traveled and urban development find that destination accessibility is more important in explaining miles traveled in cars (and hence carbon emissions) than the combination of density, design, and diversity of land use indicators [*Ewing and Cervero*, 2010]. These relationships are further complicated by age structure (see below). For example, *Liddle* [2011] found in a macrolevel cross-country study that young adult (20–34) transport energy consumption was intensive, but for other age groups there was a negative relationship with energy consumption for this sector. That is, nations with a larger share of population over age 65 have lower carbon emission from road transport. In the developing world, the population density-GHG emission relationship is complicated by energy access. Many densely populated cities have large slum populations that lack access to electricity and modern fuels and are therefore likely to use less energy than more affluent populations with access to electricity and modern fuels [*Jorgenson et al.*, 2010].

The variation in the relationship between urbanization levels and carbon emissions also may be an outcome of empirical generality. Urbanization as typically measured may not appropriately capture the energy efficiencies from dense settlement. That is, the share of the urban population in cities may not measure density levels of the types of activities that would lead to energy-related efficiencies [*Liddle and Lung*, 2010]. Many studies have identified a positive relationship between urbanization levels and GHG emissions/energy consumption [*Parikh and Shukla*, 1995; *York et al.*, 2003; *Martinez-Zarzoso and Maruotti*, 2011]. As *Liddle* [2014, p. 301], suggests, however, perhaps this "association is entirely a function of income's/development's positive association with both urbanization and energy/emissions." The countervailing effects of increased energy use from larger urban share populations but greater energy efficiencies from dense settlement might explain why some empirical studies have found a small or insignificant influence of urbanization on energy use and associated GHG emissions in aggregate [*Jorgenson and Clark*, 2010, 2012; *Liddle and Lung*, 2010; *Fang et al.*, 2012]. It is even plausible that energy/electricity consumption could cause urbanization. That is, migration motivated by the improved quality of life that the energy/electricity may bring means that access to energy causes urbanization [*Liddle and Lung*, 2014]. Further research is needed to better understand where, why, and how population growth and changes in density may influence carbon emissions.

4.2. Demographic Shifts Associated With Urbanization Influence Energy Demand and GHG Emissions

The type of people who are living in cities—in addition to the number and density—also shapes the relationship between urbanization and the carbon cycle. Aging is an important demographic characteristic with implications for energy use and associated GHG emissions [*Cohen*, 2010]. Economic activity levels vary over a person's lifetime, and mobility patterns and energy consumption adjust to changing household needs, time use, and expectations [*Wilkes*, 1995]. For example, *Liddle and Lung* [2010] find a positive correlation between age and GHG emissions among young adults (aged 20–34) and a negative correlation among older adults (aged 35–64) [see also *Menz and Welsch*, 2012]. On the other hand, *Dalton et al.* [2008] and *O'Neill et al.* [2010] find a negative correlation between age and GHG emissions, arguing that population aging will reduce GHG emissions in most developed countries as it will slow productivity. Similarly, *O'Neill et al*. [2012] find that the aging process alone can reduce emissions in the long term (100 year timeline) by up to 20%, particularly in industrialized regions.

At the household scale, the evidence that aging affects energy use and GHG emissions is mixed [*Lariviere and Lafrance*, 1999; *Lenzen et al.*, 2004]. Age structure and household size together affect transportation and residential energy use [*O'Neill and Chen*, 2002; *Liddle*, 2004]. It is worth noting that population aging is happening simultaneously with urbanization, to the extent that UN-population projections estimate that 25% of populations will be over the age of 60 by 2050, compared to 10% in 2000. How aging and urbanization will interact to shape carbon emissions is less well understood.

Household size is also an important quality of urban populations that affects the relationship between urbanization and the carbon cycle. Generally speaking, larger households have relatively lower per capita energy use because of efficiency and economy of scale benefits [*Liddle*, 2004; *Pachauri*, 2004]. Additionally, urban populations typically have smaller household sizes than rural populations, and household size is decreasing globally [*Liu et al.*, 2003]. As such, urbanization and the accompanying decreasing household size in urban areas may have a different impact on the carbon cycle than decreasing household size in rural areas. The magnitude of this difference, however, has been unexplored.

4.3. Behavioral Aspects Influence Energy Demand and GHG Emissions

Psychologists, economists, and other scholars argue that understanding consumer behavior is crucial to identifying and changing the impact that society has on the environment. For example, changing behavior is needed because technical efficiency gains resulting from energy efficiency (appliances, home insulation, and water saving devices) can be overtaken by consumption growth [*Midden et al.*, 2007]. Moreover, while people are less likely to reduce their energy use and hence GHG emissions when saving energy involves high costs (money, effort, or convenience), researchers have identified that well-being and ecologically responsible behavior are not incompatible: one can be both happy and live sustainably [*Brown and Kasser*, 2005].

Behavioral researchers ask why people consume what they do, what factors shape and constrain choices and actions, and what can encourage more sustainable behaviors and lifestyles. The study of consumer behavior in regards to sustainability, however, is far from straightforward. There are multiple models of human behavior that provide enormous complexity and a diverse range of influences that explain behavior. In an excellent review, *Jackson* [2005] identifies over 20 different social psychological theories in this area, each with a rich background and sets of empirical findings.

Originally, behavioral studies were based upon the rational choice model which predicts that individuals behave in such a way as to maximize their expected benefits (utility) through a cost-benefit analysis. Social behavior, in this model, is an emergent property of the collection of individuals maximizing their individual utility [for a review, see *Scott*, 2000]. While powerful in its simplicity, social science research focusing on behavioral characteristics moves beyond rational choice theory to more integrated models [*Stern*, 2000]. Recent research suggests that individual actions are constrained by larger forces (technological, economic, demographic, and institutional), individuals' actions also depend upon attitudes and values, mindfulness, abilities and opportunities, lifestyles, and habits or routines [*Abrahamse et al.*, 2005; *Jackson*, 2005]. Debates remain, however, on the extent to which and the processes by which different components of behavior shape environmental outcomes; research demonstrates that these microlevel variables are indeed important to motivating sustainable consumption [*Spangenberg and Lorek*, 2002]. Nevertheless, even though some argue that the larger factors "lock in" consumers to specific consumption patterns [*Sanne*, 2002], behavioral studies demonstrate that changing behavior, notwithstanding larger forces, can reduce overall human impact [*Abrahamse et al.*, 2005]. We expand upon the research in some of these areas below.

Social norms and values can induce people to change behavior [*Thøgersen and Olander*, 2002] and encourage them to conserve energy [*Schultz et al.*, 2007]. In the Netherlands, researchers found that socio-demographic variables determine household energy use, and households of higher income and households with larger size tend to have higher energy use. On the other hand, changes in household energy use appear to be associated with psychological factors (attitude, personal norm, awareness of consequences). Higher levels of perceived behavioral control and lower levels of responsibility were associated with greater energy savings [*Abrahamse and Steg*, 2009]. Similarly, *Allcott* [2011] provides evidence from randomized field experiments for nearly 600,000 households that nonprice interventions, in the form of energy reports that compare energy use with neighbors and provide energy conservation tips, can substantially and cost-effectively change consumer behavior in the United States. Households in the highest decile of pretreatment consumption that received reports reduced their consumption by 6.3%, but the lowest decile of pretreatment consumption reduced consumption by only 0.3%.

Mindfulness is a quality of consciousness that denotes a receptive attention to and awareness of ongoing internal states and behavior [*Brown and Ryan*, 2003]. Research has found that mindfulness is associated with lower materialism and a tendency toward less consumption (spending) activity over time [*Brown and Ryan*, 2004]. Mindfulness has also been found to promote ecologically responsible behavior in adults in the United States [*Brown and Kasser*, 2005].

Lifestyle choices include preferences such as for large homes, heated pools, good schools, etc. Lifestyle-related GHG emissions are reflected in both production and consumption patterns. For example, lifestyle GHG emissions can be produced from space heating and driving vehicles as well as through the global supply chain from the production of final goods and the purchase of services. In a recent study, using geo-demographic (or analysis of people by where they live) consumer segmentation data, *Baiocchi et al.* [2010] found that among 56 lifestyle groups in the UK, CO_2 emissions can vary by a factor of between 2 and 3. Another study in Finland connects lifestyle with urban form and GHG emissions and suggests that while direct emissions from transportation and housing energy slightly decrease with higher density, the reduction can be easily overridden by sources of indirect emissions [*Heinonen et al.*, 2013]. That is, indirect or lifestyle emissions, which include housing type, commuting distances, goods and services consumption, social contact, and the organization of everyday life, can overwhelm the efficiencies provided by dense settlement form.

There is still a large debate on how environmental behavior is shaped and to what degree values and actions align, given the frequent gap found between intentions and behaviors [*Thøgersen and Olander*, 2002]. There is increasing agreement in the sustainable consumption literature that reducing carbon emissions will require substantial increases in carbon efficiency and changes in the way people live and consume. Researchers call for integrating values, attitudes, behavior, and lifestyles into, for example, population environment research efforts [*Curran and de Sherbinin*, 2004]. This integration is providing interesting and important results, although researchers have only begun to explore interdisciplinary approaches connecting behavioral approaches to energy use and conservation [*Steg*, 2008].

4.4. Economic Shifts Associated With Urbanization Influence Energy Demand and GHG Emissions

The wealth and income of urban populations also significantly influence the relationship between urbanization and the carbon cycle. The majority of research has found that wealth and income lead to increased per capita energy use [*Kraft and Kraft*, 1978; *Kahn*, 2009; *Satterthwaite*, 2009; *Weisz and Steinberger*, 2010]. For example, generalized studies of cities undergoing development processes find a positive correlation between income and GHG emissions [*McGranahan et al.*, 2001]. Cross-national comparisons of urban GHG emissions and local or regional GDP demonstrate that income covaries with GHG emission levels [*Sovacool and Brown*, 2010; *Hoornweg et al.*, 2011; *Kennedy et al.*, 2011; *Marcotullio et al.*, 2013b]. At the household level, *Weber and Matthews* [2008] find a positive relationship between income and CO_2 footprints in the United States. Household-level studies in a many countries (Netherlands, India, Brazil, Denmark, Japan, and Australia) have also found positive correlations between income and energy use [*Vringer and Blok*, 1995; *Wier et al.*, 2001; *Pachauri and Spreng*, 2002; *Cohen et al.*, 2005; *Lenzen et al.*, 2006; *Dey et al.*, 2007].

Despite agreement on the positive relationship between income and energy use, however, decades of study have produced diverse and inconclusive findings on the potential for nonlinear relationships and interaction effects [for reviews, see *Ozturk*, 2010; *Payne*, 2010a, 2010b]. Urbanization is often associated with modernization and economic development, and thus income levels and energy demand typically rise with urbanization. For instance, *Jiang and Lin* [2012] compared China's urbanization and industrialization process with those of the United States and Japan, finding that energy demand is highest during the rapid phase of urbanization and industrialization, but thereafter drops off, similar to what one would find in an Environmental Kuznets curve relationship [*Grossman and Krueger*, 1995].

However, the level of development may condition the effect of economic and income growth on urban energy demands. *Poumanyvong and Kaneko* [2010], for example, find that nations with low income levels experience decreasing energy use per capita with urbanization, which may be due to fuel switching. That is, urbanization could increase household income, facilitating a rapid transition to modern fuels which curbs emissions and aggregate energy use [*O'Neill et al.*, 2012]. Achieving this interactive effect likely requires that energy policies be put in place to facilitate energy source substitution [*Bailis et al.*, 2005]. By contrast, urbanization in medium- and high-income countries is associated with increasing energy use per capita but the impact of urbanization on aggregate GHG emissions is most pronounced in middle-income countries [*Poumanyvong and Kaneko*, 2010]. The carbon footprints of cities vary substantially even at similar levels of energy use, revealing the importance of local energy mix as a driver of GHG emissions [*Brown et al.*, 2008]. The complexity of the relationship is exacerbated by the ongoing efforts to "decouple" energy demand and income growth by using income gains to invest in low-carbon energy sources and alternative transportation modes.

Many of these studies also find that at similar income levels, other socio-demographic characteristics play a role in explaining energy consumption, including, inter alia, education, age, place of residence, and household type. Further, while income is important, scholars find that economic structure also influences urban energy use and GHG emissions. For example, cities that are dependent on energy-intensive industries are likely to contribute higher total and per capita GHG emissions than those whose economic base is in the service sector [*Hoornweg et al.*, 2011]. A service-based economy can generate the same income with lower energy demand than a production-based local economy, which is one reason urban per capita energy use in advanced, service-oriented economies is lower than national averages [*Poumanyvong and Kaneko*, 2010; *Marcotullio et al.*, 2013a]. The levels of energy and GHG emissions from industrial centers increase further if the energy supply mix is carbon-intensive [*Parikh and Shukla*, 1995; *Sugar et al.*, 2012]. At the same time, however, cities with service-based economies (such as Tokyo) have large indirect emission levels, not typically accounted for in urban-level analysis [*Dhakal and Imura*, 2004]. If the emissions from consumption demands, for example, are included in local inventories, the residential carbon footprint from urban areas with large service economies may increase significantly [*Kennedy et al.*, 2009; *Hillman and Ramaswami*, 2010; *Ramaswami et al.*, 2011].

Cities also assume different functional niches within larger regional and global urban systems [*Lo and Yeung*, 1998; *Sassen*, 2006] with implications for energy demand and GHG emissions. For example, trade, foreign direct investment (FDI), and the movement of people shape urban development and the relationship between urbanization and the carbon cycle [*Lo and Marcotullio*, 2001]. Cities often specialize within the global economic system, with some urban centers focusing on manufacturing and others on commercial or administrative functions. As mentioned previously, manufacturing and industrial urban areas typically have higher carbon signatures than those of global command and control centers, known as "global cities." *Schulz* [2010], for example, demonstrates the significance of international trade in oil products for Singapore's domestic and embodied energy use is approximately 173 GJ/capita, but total energy imports to the city are in the order of 1490 GJ/capita.

In many cases, urban carbon footprints experience "leakage" when emissions from urban teleconnections [*Seto et al.*, 2012; *Seto and Reenberg*, 2014] are off-loaded to other areas. That is, while energy savings can be realized from dense urban developments through, for example, more efficient personal mobility or space heating, emissions from the production of goods consumed in urban areas is found elsewhere. These are sometimes termed "deemed" emissions [*Lebel et al.*, 2007]. For example, in eight US cities *Hillman and Ramaswami* [2010] found that airline and freight transport plus embodied energy of food, fuels, cement, water, and wastewater added an additional 7 $MtCO_2e$ to per capita GHG emissions increasing average per capita urban emissions by about 47%. *Dhakal and Imura* [2004] indicate that Tokyo's "indirect" emissions, or those emissions embodied in material goods consumed in the city, but not produced there, are approximately equal to if not more than its direct emissions for 1990 and 1995. For the United States in 2004, international trade resulted in 30% of total US household CO_2 leaking outside the United States [*Weber and Matthews*, 2008]. The identification and analysis of urban teleconnections in regards to GHG emissions is a new area of research [*Ramaswami et al.*, 2012].

4.5. The Political and Institutional Features of Cities Influence Energy Demand and GHG Emissions

Political conditions and institutional structures influence the energy use and GHG emissions associated with urbanization in multiple ways. Cities are terrains of political struggle, and people are part of the urban infrastructure. Cities and their territories are constructed politically and reproduced through everyday acts and struggles around consumption and social reproduction [*Jonas and Ward*, 2007]. Practices and politics of care influence energy demand and GHG emissions, such as the social movements that have enabled cities to pass climate change action plans. However, direct empirical results demonstrating causal linkages between urban political and institutional features and energy demand and GHG emissions are few.

Growth politics help to shape urban form, transportation patterns, and ultimately determine the levels and types of resources necessary to sustain urbanization processes. Growth politics refers to the conflict and contestation surrounding land use change and economic expansion in urban areas. Growth politics and conflicts are common in both developed and developing countries [*Sager*, 2004; *Aguilar and Santos*, 2011; *Ju and Tang*, 2011]. Given the association between urban form and transportation patterns, the outcome of these conflicts can influence energy use and GHG emissions [*Stone*, 2009].

A result of the various political factors driving energy use and GHG emissions associated with urbanization is often a heterogeneous distribution of access to energy and transportation infrastructure both between urban and rural areas and within urban areas. For example, urban populations in India generally have higher levels of access to commercial energy forms than rural population [*Pachauri*, 2004; *Pachauri and Jiang*, 2008]. The *UN-Habitat* [2003] estimates that large swaths of the world's urban populations, totaling approximately 800 million people globally, do not have access to adequate energy sources. This "energy poverty" is also a real and present problem for the urban poor in high-income countries and in many former communist states [*Weisz and Steinberger*, 2010]. In the developed world, the inability of local power brokers in New York City, for example, to develop highways in the urban core [*Caro*, 1975] had lasting effects on transit use and subsequent motor vehicle use. The political dynamics within cities and even within neighborhoods can significantly structure alternative energy outcomes [*Aylett*, 2013].

In addition to political factors, the ways in which resources are governed can shape urbanization processes and associated energy use and GHG emissions [*Bulkeley*, 2013]. For example, zoning regulations and land use plans help to determine urban form, leading to a variety of interconnected outcomes, which can shape energy use and net GHG emissions. Differential urban form can lead to low or high heat island impacts (and concomitant air conditioning energy use), varying quantities of urban-vegetation carbon sinks, and influence the primary modes of transportation. Such zoning and land use plans are frequently implemented by city governments in the developed world [*Runfola and Hughes*, 2014]. Yet, the increasingly fragmented nature of local government, such as that in the United States, impedes the coordination of land use decision making across municipalities and fuels suburban sprawl [*Lewis*, 1996].

Governance includes institutional capacity, or the financial, scientific, legal, and human resources required to shift consumption and production patterns in the city [*Romero-Lankao et al.*, 2013]. Some cities have the institutional capacity to take steps to reduce the vehicle miles traveled within their territories through infrastructure design, pricing of various components of the transportation system, and availability of alternative transportation, while others cannot. Some cities have introduced building codes with hopes that these regulations will reduce energy demand. Whether urban decision makers decide to take such steps will depend on the political conditions and governance systems that are in place. Governance and institutional capacity are frequently scale- and income- dependent, meaning they tend to be weaker in smaller cities and in low-income settings [*Grubler et al.*, 2012].

An important local governance issue includes the organization and control of energy markets at the urban level, including the establishment of monopolies or cartels, the pricing of fuel within a free-market or highly regulated context, and the openness of trade. Some municipal utilities can decide whether or not to introduce energy efficiency measures and incentive programs for energy demand reduction. The

United States has a long history of investing in demand side measures for energy conservation, with mixed success [*Loughran and Kulick*, 2004]. Municipal utilities can also invest in alternative energy sources that reduce the carbon-intensity of energy consumption, but people's willingness to pay for such measures varies widely [*Zarnikau*, 2003]. Where urban and local governments do not have the mandate to control energy markets and utilities, other organizations and institutions direct outcomes, which can affect energy access, use, and subsequent GHG emissions.

At the national scale, many countries have policies and institutions that shape the urbanization process. For example, during the histories of some of the largest populated nations (Brazil, Russia, India, China, and South Africa; BRICS), governments have at times caused interruptions and impediments in migratory movements to urban areas. These efforts are not unique as the proportion of countries having policies aimed at slowing down migration to urban areas increased from 47 to 69% between 1976 and 2009 [*McGranahan and Martine*, 2014]. During recent years, China has embraced urbanization after carefully restricting the process in the past. China's "radical" urbanization has underpinned the country's economic growth and has been key to the nation's economic growth strategy [*McGranahan et al.*, 2014] and likely underpins increases in energy consumption and GHG emissions [*Shen et al.*, 2005; *Jiang and Lin*, 2012].

Climate governance increasingly operates at multiple and increasingly overlapping scales. For example, urban political actors act through numerous transnational networks to develop and implement climate change plans, such as Local Governments for Sustainability (ICLEI), the Clinton Climate Initiative's C40 program, and the World Mayors Council for Climate Change. These networks represent a shift in the way that GHG emissions are governed both locally and globally [*Bulkeley and Betsill*, 2003; *Betsill and Bulkeley*, 2006]. Importantly, however, local climate change actions have the potential to reshape cities in ways that further marginalize disadvantaged urban populations, a dynamic that has been understudied by social scientists [*Bulkeley*, 2010; *Hughes*, 2013].

Finally, path dependence, including energy resource endowments, has an important influence on the trajectory of urbanization and subsequent energy use and GHG emissions [*Romero-Lankao et al.*, 2014]. Path dependence is the tendency for previous decisions to affect current and future choices [*Arthur*, 1989]. As *Chester et al.* [2014] note, urbanization tends to produce physical forms and institutions that are not easily transformed. Moreover, cities follow trends within the larger nation. In terms of energy consumption, cities often draw from the national electricity grid. Some countries with well endowed coal reserves (United States, China, and Russia) have large numbers of coal-based thermal power plants. Some localities have district heating and cooling infrastructures, which allows large economies of scale, cogeneration and energy-efficient systems, such as New York City, Central and Eastern European cities. Once infrastructure is built, it becomes fixed and helps to determine future choices, sometimes called "lock-in" [*Davis et al.*, 2010]. As urban areas grow and include larger areas of differential land use, population and employment density, changing fossil fuel consumption patterns becomes more difficult. Some scholars explore these patterns and trends deploying socio-technical transition theory [for a review and critique, see *Lawhon and Murphy*, 2011], which has potential for identifying when lock-in might occur and the antecedents of and triggers to threshold effects. The notion of thresholds, tipping points, and critical transitions in natural science is a new and exciting field, but as applied to the urban socio-institutional context requires further research to determine where it is most applicable [*Scheffer et al.*, 2009, 2012; *Scheffer*, 2010].

5. Conclusions: Research Priorities

There is a long tradition of urbanization research in the social sciences. Moreover, a growing body of social science literature has examined elements of the relationship between urbanization and the carbon cycle. However, this review finds that energy use and subsequent GHG emissions have not been fully integrated into the social science of urbanization. In some areas, the relationship between urban social processes (such as governance) and energy use are inferred rather than demonstrated. In other areas, there has been much empirical work only to generate consensus at the broadest levels without strong theoretical underpinnings. In almost all cases, scholars have worked within disciplinary boundaries at the expense of developing a holistic, process-based definition of urbanization. Importantly, with the exception of a few efforts, scholars examine cities and urban growth, rather than the process-oriented and context-dependent concept of urbanization. Hence, while various researchers have provided glimpses of urban dynamics these studies are partial and underspecified.

While these results are not surprising given the long and deep history of social science disciplines and the relative novelty of the topic, we argue that the way societies organize (spatially and socio-ecologically) now and into the future is the greatest challenge currently facing humankind [*Solecki et al.*, 2013]. Not only is it important to understand changes in the spatial organization of population, but even more critical is understanding the ways in which the characteristics of dense settlements and activities, their economies, their population dynamics, and their governance can lower the impact of urbanization on the carbon cycle. This we believe should be a priority goal for researchers. While we identified areas for further research throughout the above discussion, we present an integrated research agenda based upon five priorities for small teams or researchers working as part of larger interdisciplinary efforts.

5.1. Develop and Use More Comprehensive Conceptual Frameworks of Urbanization Processes, Drivers, and Connections to the Global Carbon Cycle

The existing social science literature is rife with partial explanations and limited or conflicting evidence regarding the impacts of urbanization on the carbon cycle. Few studies explore the relative and interactive effects of socio-institutional systems on the relationship between urbanization and the carbon cycle, fewer still do so at a global scale. Examining isolated drivers has limitations as it does not generate an adequate understanding of contemporary transformations that is transferable to policy development and risks omitting important leverage points for change.

We argue for a multidimensional, process-based conceptualization of urbanization and for efforts to disentangle the roles of various features of socio-institutional subsystems in influencing the carbon cycle. We need to explore the urbanization process and develop a science that can yield laws and principles based upon an understanding of how this complex process operates. At the same time, we recognize the need for more careful explications of the mechanisms embedded within these processes, including how the individual dimensions of urbanization interact and co-evolve with energy use and carbon systems. Such thoughtful theorizing should help bring coherence to the complex and often conflicting social science research that has so far emerged and direct future research endeavors.

Developing such frameworks requires that social scientists prioritize theory development and primary data collection (of various kinds) that elucidate the relationships, mechanisms, and interactive effects that underlie the relationship between the social processes of urbanization and energy use.

5.2. Examine Differences in Socio-institutional Processes of Urbanization and Their Impacts on the Carbon Cycle

Not only do researchers need to shift away from static understandings of the relationship between cities and the carbon cycle, it is also necessary to develop comparative research on how dynamic changes in socio-institutional subsystems lead to new and different patterns of urbanization that have varying consequences for the carbon cycle. Not enough attention has been given to the unique social-political characteristics and histories of urbanization in the developing world. For example, the urban transition in Latin America was associated with import-substitution industrialization where urban economies were unable to absorb a rapidly growing labor force. Urban authorities had little to no means to provide universal access to high-energy consumer infrastructures [*Romero-Lankao*, 2007]. By contrast, urbanization and industrialization have been largely uncoupled in Sub-Saharan Africa [*Parnell and Walawege*, 2011] with even more exaggerated energy infrastructure provision needs. These differences in the character of urbanization affect the trajectories of urban energy use and carbon emissions by country and region. Understanding the dynamics of these trends will help to inform options for the transferability of applicable sustainable urban development policies.

More research needs to focus on understanding key differences in the character of contemporary urbanization and the implications for future global carbon dynamics. We need to understand the differential compositions of urban populations, economic shifts that accompany urbanization, and governance of urbanization and their relationship to energy use and GHG emissions. Useful ways forward include: (1) development of a typology of urbanization processes that distinguishes contemporary from historic patterns; (2) projections of alternative urban futures given current and possible changes in the drivers and subsystems of urbanization such as changing economies and policies; and (3) projections of alternative carbon futures that derive from these alternative urbanization futures. To adequately project alternative urban and carbon futures, researchers should also seek to better understand (4) how the various drivers interacted historically to produce the urbanization processes we see today, and (5) which drivers have the most influence on the relationship between urbanization and the global carbon cycle. Particular attention to path dependency and how prior choices may "lock-in" carbon-usage patterns, constraining future options, is critical. This requires more comparative research projects examining changes in social processes of urbanization and consequences for the carbon cycle. Such efforts would then be well positioned to inform policy discussions of the behavioral, institutional, and economic changes needed to achieve socially desired goals.

5.3. Investigate Intra-urban Differences in Urbanization Processes and Subsystems Relating to Carbon

Most studies of urbanization ignore the social and physical diversity that exists within cities and how these differences generate consequences for energy use and GHG emissions. In New York City, for example, the average carbon footprint is approximately 6.5 tons per capita [*Dickinson et al.*, 2012] but represents emissions from residents living in buildings holding the highest concentration of billionaires in the world and those of homeless individuals living less than a mile away [*Gross*, 2006]. Using a mean to describe GHG emissions levels for an entire urban area obscures the rich variation in contributing sources, ranging from residences to commerce, industry, transport, waste management, agriculture, and forestry, and in turn hinders our ability to understand relevant drivers [*Chester et al.*, 2014]. For example, in a study that examined areas by zip-code, those households within core metropolitan regions in the United States had relatively low carbon footprint (tons CO_2/household), while households in suburban areas have higher carbon footprints than the national average and from those in rural and micropolitan areas [*Jones and Kammen*, 2014].

While environmental justice research has shown greater environmental impacts on ethnic minorities and the poor in many cities, it is less clear how group-based inequalities may impact the carbon cycle. Likewise, social groups do not settle in the same spatial patterns across regions. For example, historically high-income households tended to be located in the urban periphery of North American cities, while low income households tend to be located in the periphery throughout Latin America. Scholars need a better understanding of how location decisions of residences and businesses impact access to and use of energy [*Anas et al.*, 1998], and how the urban spatial structure and concomitant land use produces distinctive intra-city carbon footprints [*Milesi et al.*, 2005]. Social scientists, working individually or as part of larger teams, can play an important role in identifying the implications of GHG emissions mitigation and energy demand reduction for social justice given the diversity of social patterns, conditions and populations within cities. Focusing on spatial disparities will also help to clarify the effects of social-institutional systems on the carbon cycle.

5.4. Generate a Deeper Understanding of the Political and Policy Dimensions of Urbanization's Influence on the Carbon Cycle

We currently have a limited understanding of who major stakeholders are, what interests are at play, and how they mobilize (or not) to influence the energy use and GHG emissions associated with urbanization. Moreover, we do not have a good understanding of what works, from a policy perspective, to reduce the energy use and GHG emissions associated with urbanization, how best to interface with decision makers, and how to learn lessons from city to city.

Examinations of the social processes of urbanization should incorporate the political discourses surrounding fossil fuels, land use, and lifestyle choices when accounting for variation in energy use outcomes. For example, recent research has examined the politics and power dynamics engaged in resistance to low-carbon transitions [*Geels*, 2014], which could be examined in an urban context. A directed effort to embed studies of energy consumption in the political and institutional aspects of urbanization is necessary. We cannot presume that past patterns of Western urbanization, based as they were on energy consumption and hence carbon emissions, offer the best insights into future patterns of urbanization. Instead, social scientists must carefully explore how possibly hidden assumptions about the availability of cheap carbon empirically affect urbanization. A greater deployment of policy analysis tools, methods, and theoretical approaches (both quantitative and qualitative) would also contribute to an improved understanding of what interventions work, when, in order to influence the trajectory of urbanization as it relates to energy use.

5.5. Collect and Disseminate Urban-Scale Data

A key limitation for progress in social science urbanization research is the lack of comparable and spatially explicit data on the social, political and economic features of cities, their carbon sources and sinks, and the direct and indirect flows of energy between urban centers and between hinterlands and urban centers. First, there is little long-term (i.e., 30 years +) information on how, when, why or where urbanization has occurred, and very limited infrastructure in place to begin such data collection and dissemination. Such data will be critical for drawing broad-scope conclusions regarding the future of urbanization and the impacts of changing drivers on alternative urban futures. High spatial resolution, and broad-scope data for inter- and intra-urban analysis and *effective interdisciplinary methods for connecting these data to social and institutional features of urbanization* are critical to systematic studies of the ways in which socio-institutional systems shape the relationship between urbanization and the carbon cycle.

Second, we need spatially explicit indicators of the important social and institutional qualities that accompany past, present and future patterns of urbanization. If we are to understand the implications of urbanization for the carbon cycle, and opportunities for minimizing urbanization's impacts, the research community must develop appropriate indicators from which to compare experiences and understand trade-offs.

While long term, large data set collection studies are important, we also need research that connects an understanding of the qualities of urbanization to spatially explicit data on carbon sources and sinks to better understand impacts of the various qualities of urbanization on the global carbon cycle and from which to estimate alternative carbon futures. In this regard, geographic information systems, satellite imagery, and increased computational power and storage have dramatically expanded our capacity to study urbanization and the carbon cycle in the United States (see recent initiatives by the *EPA* [2014], NASA/DOE VULCAN initiative [*Gurney et al.* [2009]], and the *USGS EarthExplorer* [2014]). Efforts to harmonize data collection are improving comparability of data worldwide (see the Global City Indicators Facility [*GICF*, 2014], International City/Council Management Association [*ICMA*, 2014], and urban indicators [*World Bank*, 2014]). Despite the opportunities these and related initiatives present, they are all heavily limited in terms of spatial scale, scope, or temporal extent. In the absence of spatially explicit and comparable intra-urban carbon emissions data, researchers may use proxy measurements such as criteria air pollutants (i.e., ozone, particulate matter, and carbon monoxide) that also derive largely from the burning of carbon-based energy for fuel.

In general, social scientists, working in small teams or with large interdisciplinary groups, need to develop creative ways to collect and analyze data including large and small sample size comparative studies and case studies, so as to elucidate the details of how urbanization operates within a particular context and how socio-institutional dynamics help determine energy use, fossil fuel consumption, and carbon emissions.

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