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A critical knowledge pathway to low-carbon, sustainable futures: integrated understanding of urbanization, urban areas and carbon

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- We need integrated, coproduced approaches to urbanization, urban areas, and carbon
- Urbanization uncertainties are of similar magnitude to carbon uncertainties
- Lock-ins in urbanization, cities, and carbon constrain low-carbon transitions

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A critical knowledge pathway to low-carbon, sustainable futures: Integrated understanding of urbanization, urban areas, and carbon

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Abstract Independent lines of research on urbanization, urban areas, and carbon have advanced our understanding of some of the processes through which energy and land uses affect carbon. This synthesis integrates some of these diverse viewpoints as a first step toward a coproduced, integrated framework for understanding urbanization, urban areas, and their relationships to carbon. It suggests the need for approaches that complement and combine the plethora of existing insights into interdisciplinary explorations of how different urbanization processes, and socio-ecological and technological components of urban areas, affect the spatial and temporal patterns of carbon emissions, differentially over time and within and across cities. It also calls for a more holistic approach to examining the carbon implications of urbanization and urban areas, based not only on demographics or income but also on other interconnected features of urban development pathways such as urban form, economic function, economic-growth policies, and other governance arrangements. It points to a wide array of uncertainties around the urbanization processes, their interactions with urban socio-institutional and built environment systems, and how these impact the exchange of carbon flows within and outside urban areas. We must also understand in turn how carbon feedbacks, including carbon impacts and potential impacts of climate change, can affect urbanization processes. Finally, the paper explores options, barriers, and limits to transitioning cities to low-carbon trajectories, and suggests the development of an end-to-end, coproduced and integrated scientific understanding that can more effectively inform the navigation of transitional journeys and the avoidance of obstacles along the way.

1. Why Urbanization, Urban Areas, and Carbon?

In recent years, the relationships between urbanization, urban areas, and the carbon cycle have generated increased interest in research and policy circles for a variety of reasons. We have urbanized our planet to an unprecedented level. The concentrations of infrastructure, economic and social activities, and populations in cities create growing demands for fossil fuels and carbon-intensive materials to build and power domestic services, commercial buildings, industrial processes, telecommunications systems, water provision, waste production, travel, and a seemingly endless array of other uses. By 2050, the global urban population is expected to increase from 3.6 billion to over 6 billion, mainly in low- and middle-income countries [*United Nations Department of Economic and Social Affairs*, 2010]. With urban extent forecast to triple between 2000 and 2030, more urban land expansion will occur during the first three decades of the 21st century than in all of human history [*Seto et al*., 2012a]. This projected growth in urban land use creates an increased urgency to develop an integrated understanding of urbanization and urban areas in the global carbon cycle. This urgency is highlighted by the fact that even though urban areas occupy <3% of the total global land surface, they have global-scale impacts on natural resources, social dynamics, human well-being, and the environment. They are responsible for between 67 and 76% of final energy use, globally and between 71 and 76% of CO_2 emissions [*Seto et al*., 2014]. The accelerating rate of global urbanization coupled with a growing recognition that urban areas account for a large and increasing proportion of global greenhouse gas (GHG) emissions has made the need for further research in this area evident.

As mitigation of carbon emissions has become an increasingly important element of urban climate change policy making, many cities have declared their commitment to reducing their reliance on fossil fuels in an effort to curb GHG emissions. Hundreds of these cities are now participating in Local Governments for Sustainability (ICLEI), the C40, 100 Resilient Cities, US Mayors Commitment Network, and other transnational and national networks [*Bulkeley*, 2010; *Carmin et al*., 2012]. However, a gap exists between their pledges to achieve GHG emission reduction targets and the real mitigation potential of their actions, which are often limited based on local government control and jurisdiction [*Aylett*, 2014]. Thus, as a handful of European and US studies [*Dixon and Wilson*, 2013; *Reckien et al.*, 2014] illustrate, many urban mitigation actions fall short of the emission reduction targets needed to avoid a 2°C increase in global mean temperature. The global impact of urban mitigation efforts is also unclear, due to little systematic reporting on implementation, and limited evidence on differential mitigation potential for different urban areas and socio-ecological and technological contexts. GHG emissions within these urban contexts, along with any mitigation results that they might achieve, can best be understood through knowledge coproduced by researchers and practitioners who create a thorough quantification of city-level carbon emissions [*Hutyra et al*., 2014] as they relate to the key urbanization processes driving energy and land use [*Marcotullio et al*., 2014], and an evaluation of progress toward mitigation targets.

Despite decades of independent lines of research on the global carbon cycle, urban areas, and urbanization, we have barely scratched the surface in our efforts to understand the many processes and interconnections through which energy and land uses driven by urbanization induce changes in carbon flows globally, and which low-carbon interventions are effective where, and why. Some of the sources of GHG emissions in urban areas are associated with fossil fuels usage to produce energy, releasing CO_2, and when waste disposal creates methane. Because of the concentration of populations, energy use, and waste within urban areas, carbon flows from urban areas into the atmosphere are key drivers of global climate change. Here we distinguish between urban areas as places or socio-ecological and technological systems and urbanization as a series of interconnected processes and transitions defining how humans interact with each other and the environment; however, we are most interested in the interrelationship between the two as they relate to carbon emissions and drive environmental impacts. Rooted in the context of urban area as place, the development pathways driven by urbanization are characterized by changes (shifts) in economic dynamics and capital accumulation, demographics, culture and political influence, built environment and infrastructure, and by the transformations of ecosystem services and functions implied by these processes [*Marcotullio et al*., 2014 and Table 1].

While it is clear that urban areas are expanding rapidly worldwide and their uses of energy and land are key elements shifting the global carbon cycle toward higher GHGs, urban carbon research has been dominated by relatively few comparative case studies, most often focused on quantifying carbon emissions in large cities in high-income countries [e.g., *Kennedy et al*., 2009] or on China [*Sugar et al*., 2012]. Studies of cities in low- and middle-income countries have been few and limited in scope [e.g., *Chavez et al*., 2012], and we have a very limited understanding of urbanization patterns and the types of urban areas that may operate across space and over time. We do know, however, that contemporary urbanization, especially in low- and middle-income countries, is significantly different, in rate, attributes, and magnitude, from the historic urbanization processes that occurred in Europe, North America, and Latin America [*Romero-Lankao*, 2007; *Satterthwaite*, 2007; *Marcotullio et al*., 2013a, 2013b]. There can be little doubt that

Table 1. A Comparison of Contemporary Research on Urbanization, Cities, and Carbon

	Engineers/Industrial Ecologists	Social Scientists	Natural Scientists
Motivation	Bridging of ecological, social, and technical domains to address the decoupling of carbon from urbanization	Understanding urbanization and its interactions with energy, land use, and GHG emissions	Quantifying carbon pools and fluxes (e.g., biota, fossil fuels) between urban systems, biota, waterways, and the atmosphere; and understanding the physical and biological mechanisms controlling fluxes
Definitions of "carbon" of urban relevance	An input (fossil fuels, renewables) that directly or indirectly supports human activities; an output (CO_2 equivalent or GHG with warming potential)	A natural resource (e.g., fossil fuels), an element embedded in materials and artifacts (e.g., cement, furniture), or a pollutant/waste (e.g., methane)	The flow, flux, or exchange of carbon among pools (e.g., materials, fuel, biosphere, hydrosphere, and atmosphere). CO_2 and CH_4 are key observational measures and land-atmosphere exchange is a high-priority carbon flow
Definition of "urbanization" of urban carbon relevance	A process shaped by growth • in the proportion of population living in cities • of urban infrastructure, i.e., paved streets, water supply and sewerage systems, electricity	A process resulting from shifts (transitions) in • population dynamics, or • economic transitions (from primary to secondary and tertiary sectors), or -modernization, or • cultural change, or • political influence of elites, or • increased social complexity	A process that alters land cover and ecosystems, and significantly concentrates and disrupts "natural" carbon flows and pools. This process is dominated by anthropogenic carbon fluxes
Definition of "urban areas" of urban carbon relevance	Metabolic systems entailing technical and socioeconomic processes that result in growth, production of energy, and elimination of waste	City and urban areas refer to a spectrum ranging from "megacities" to smaller-scale urban settlements (e.g., towns)	Terrestrial areas dominated by impervious surfaces where land cover change has occurred or the process of urbanization is ongoing. Boundaries follow various definitions associated with population density, governance, or energy intensity metrics
Selected research questions	How is urban metabolism changing? What processes in the metabolism threaten the sustainability of cities? What are the carbon impacts from life-cycle analysis (LCA) of the extraction, processing, transport, use and disposal of water, materials, energy, and nutrients?	How do the following factors affect energy use and GHG emissions: demographic dynamics, affluence, economics, and institutional settings? What triggers, opportunities, and stresses drive urban transitions? What are the opportunities, barriers, and limits to effect urban change? What are the attributes of low-carbon urban transitions?	What are the urban anthropogenic carbon fluxes and stocks? How do they change in time and space? Can we attribute carbon fluxes by process, space, and time? What factors control carbon fluxes? How can knowledge on carbon fluxes inform mitigation policies? What are the primary causes for discrepancies between research grade and regulatory or "self-reported" emission inventories? Can we reconcile "top-down" and "bottom-up" approaches to flux quantification?

Table 1. (continued)

	Engineers/Industrial Ecologists	Social Scientists	Natural Scientists
Selected conceptual model or framework	Urban metabolism: the materials flowing into an urban system, the stocks and flows within it, and the resulting outputs (pollution, waste, exports). Life-cycle analysis (LCA) of the inputs, outputs, and impacts of an urban product system throughout its life cycle	STIRPAT: a stochastic regression to quantify the impacts of population, affluence, and technology on energy use/carbon emissions in cities	Convergent data/model system capable of both characterizing process-driven fluxes between urban carbon pools most notably from the urban landscape into the atmosphere and observations that have optimized the estimated surface fluxes into consistency with atmospheric observations

the dynamics of the built environment, and socio-institutional and natural systems of these urbanizing areas present new constraints and opportunities not present in the past century of urbanization and that the coevolution of urban areas, the carbon cycle, and urbanization will likely diverge from earlier patterns. Even in high-income countries urban areas are facing new challenges such as postindustrialization, deindustrialization, population shrinkage and diversification (aging and immigration), and outdated and aging infrastructure [*Bernt*, 2009]. These trends limit in some ways the transferability of knowledge across time and regions, present alternative opportunities for sustainable and resilient alteration of energy and land usage, and increase the uncertainty associated with the role of urbanization in carbon flows globally.

Another important challenge is the fact that, as yet, there is no standardized definition of urban areas among scholars and international organizations. In fact, countries are asked by the United Nations (UN) to establish their own definitions “in accordance with their own needs” [*United Nations* (*UN*), 2008]. One of the most commonly used is concerned with urban boundaries, often politico-administrative, and defined mostly by municipalities and state territories. A second common definition is physical or morphological, given by the extent and layout of the built environment, infrastructure, and land uses of a city and describing its urban form, while a third is concerned with urban function, defined by economic, mobility, informational, and operational connections between urban cores and outside areas. The importance of this definitional challenge becomes apparent when we look at the implication of boundary definition for the amount of carbon attributed to a city. For instance, looking at US urban areas, *Parshall et al*. [2010] found that differing definitions of urban boundaries yield widely varying results in attempts to attribute energy use. With changes in these definitions, estimates of fuel consumption within cities ranged from 37% to 86% for buildings and industries and from 37% to 77% for urban road-based transportation. Similarly, *Raciti et al*. [2012] found that alternative, commonly used urban definitions can result in vegetation carbon stock density ranging from 37 ± 7 to 66 ± 8 MgC ha^{-1} and can lead to different conclusions as to the importance of biological carbon stocks and fluxes within urban areas.

In addition to the aforementioned challenges, the relationships between urbanization, urban areas, and the carbon cycle have been studied only recently and by disparate research communities, largely segregated between natural, social, and engineering sciences. This has resulted in differences in definition and scope, conflicting theories and paradigms, incompatible data and results, and a fragmentary understanding of attributes, relationships, and dynamics (Table 1). For example, urban carbon research in the natural sciences has focused mainly on quantification of carbon pools (e.g., biota, waste, and fuel) and fluxes or flows between the urban land surface and the atmosphere with particular emphasis on atmospheric monitoring [*Hutyra et al*., 2014]. However, these efforts do not address the economic growth, institutional settings, cultural values, and infrastructure that condition carbon emission through differences in energy and land use; thus, these studies have been primarily diagnostic. Engineers and industrial ecologists have developed detailed models of the flows of materials and energy that power transportation, buildings, water, waste, electricity, and other elements of the built environment [*Kennedy et al*., 2007], but tend to examine these sectors in isolation with limited attention to interactions within and between infrastructures and ecosystems, or atmospheric, terrestrial, and aquatic carbon pools [*Chester et al*., 2014]. Social scientists have developed many limited perspectives that examine the demographic, economic, political, and cultural dimensions of urbanization [*Marcotullio et al*., 2014], but have only recently begun to explore the influence of emission drivers such as demographic dynamics, affluence, and socio-political conditions [*Romero-Lankao et al*., 2009; *Liddle*, 2013; *Marcotullio et al*., 2013b], and none has yet made explicit linkages to the spatiotemporal distribution and physical and ecological controls on carbon emissions from cities.

A lack of interdisciplinary and coproduced research on the influence of urbanization and urban areas on GHG emissions profoundly limits the potential to consciously shift global carbon trajectories through planned alteration of energy and land uses. Without an improved and coproduced understanding of the diverse linkages between natural, socio-institutional, and built environment components of urban change and carbon flows from fixed to gaseous states or vice versa, it will be difficult to evaluate the potential and efficacy of mitigation solutions—from market instruments to expanded public transportation systems.

2. What Is Needed

We have an urgent need to develop an integrated and coproduced understanding of both basic and applied research questions [*Weaver et al*., 2014] focused on how urbanization processes and urban areas as places or socio-ecological and technological systems [*Chester et al*., 2014] influence energy and land use, thereby producing GHG emissions and affecting carbon flows. This integrated understanding must be explicitly linked to space/time models of land-atmosphere carbon flows (Figure 1) that can be consistently incorporated into the analysis of global carbon pools, flows, and feedbacks (e.g., to climate change). Furthermore, to be socially relevant, it must engage scientists and stakeholders or actors not only in project design but also in the exploration of the mitigation limits (e.g., lock-in) and opportunities to transition toward low-carbon urbanization pathways.

This special issue, an outcome of the 2013 Workshop on Human-Carbon Interactions in the Urban System, is an attempt to respond to this challenge. The Workshop was held on October 16–18, at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, with the sponsorship of the Carbon Cycle Interagency Working Group (CCIWG)'s U.S. Carbon Cycle Science Program, under the auspices of the U.S. Global Change Research Program (USGCRP). The main goal of the workshop was to examine the state of the science, identify the gaps in knowledge, and propose a research agenda that integrates the socio-institutional, natural, and built environment feedbacks that affect carbon dynamics in urban systems. The next three papers in the issue provide a review and outward looking research agenda from the perspective of one of three broad intellectual domains that have contributed much to our current understanding of the links between urbanization, urban areas, and carbon.

Hutyra et al. describe the history of natural scientists' interest in urban areas in recent years, and present the quantitative approaches and methods employed to diagnose historical and current fluxes and stocks of carbon within and outside urban areas, with particular emphasis on using the atmosphere as a vantage point for observations. They outline the complexities associated with quantitatively characterizing carbon flows in urban areas and the challenges ahead. They close with potential opportunities to reach out to the engineering and the social science communities to begin building a much larger, inclusive, and explanatory conceptual framework for how urbanization, urban areas, and the carbon cycle interact, and how we might understand those interactions to better inform emission mitigation strategies and the transition of cities toward sustainability.

Marcotullio *et al.* outline the contributions of social sciences to the study of the processes of urbanization that better capture carbon interactions, explain change overtime, and identify social leverage points for change. They review research trends and findings on recent and plausible relationships between urbanization, energy and land use, and GHG emissions. They identify gaps in knowledge and priority areas for future social scientific research. They also suggest a conceptualization of urbanization as a multidimensional social, infrastructural, and biophysical processes driven by changes in population, and economic and institutional dynamics across space and time. This perspective facilitates a wider spectrum of research that can connect to the engineering and the natural science communities.

Chester *et al.* synthesize state-of-the-art methods for the analysis by engineers, planners, and industrial ecologists of the carbon implications of transportation, fuels, buildings, water, electricity, and waste

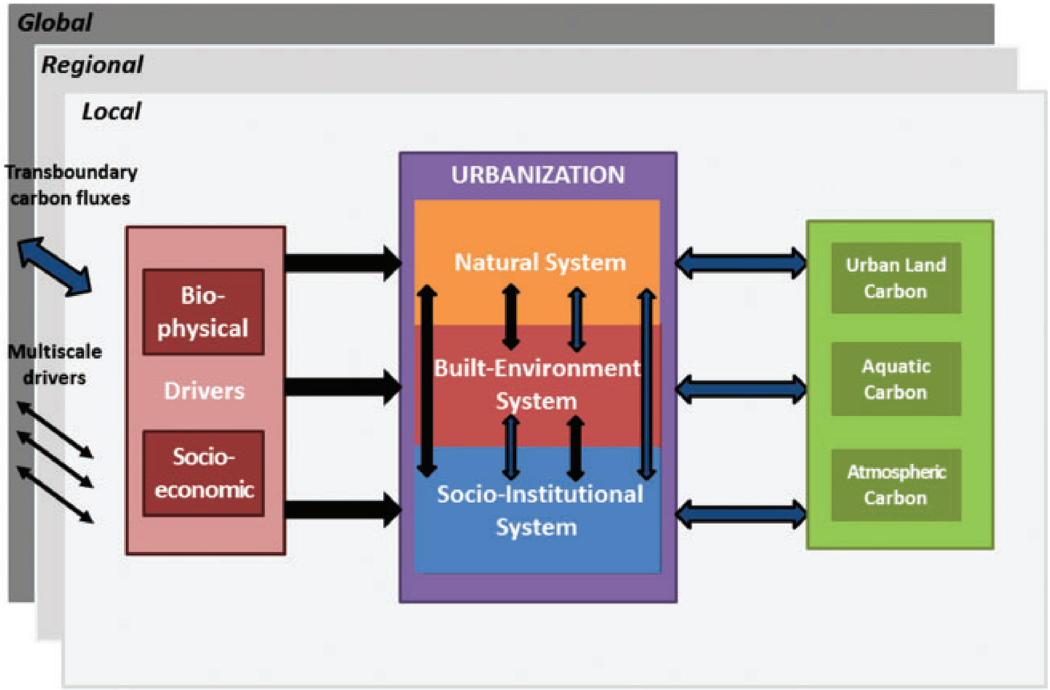

Figure 1. Conceptual framework depicting the key dynamic relationships for an improved understanding of urbanization, urban areas, and the carbon cycle. Note: Blue arrows depict links between systems and components.

systems, and find that GHG emission assessment tends to view these infrastructure systems as static and existing in isolation from socio-institutional systems. They find that despite significant knowledge of how to reduce GHG emissions from infrastructures and technologies, physical, institutional, and cultural constraints continue to work against engineering approaches. They advocate for a bridging of the ecological, social, and technical domains to achieve the decoupling of carbon from the urbanization process. Pointing to knowledge gaps that can be addressed through interdisciplinary collaboration and research coproduction, they then identify seven challenges that must be overcome in order to improve our understanding of the roles that infrastructure and technologies may play, during urbanization, and recommend a better utilization of these increasingly complex systems to promote low-carbon growth.

This synthesis paper seeks to pull some of these diverse viewpoints together as a first step toward developing a coproduced and integrated framework for understanding urbanization processes, urban areas, and their relationships to urban carbon (Figure 1) that are further elaborated in the contributing papers in this special issue.

An array of frameworks has explored the interactions between urban areas and the environment. Some have focused on a series of principles and practices that make cities more livable and environmentally friendly, i.e., more sustainable [*Alberti and Susskind*, 1996; *Roseland*, 1997]. Others have effectively used theories and concepts from ecology to explore key, long-term interactions between urban activities and ecological systems within and outside urban areas [*Grimm et al*., 2000; *Pickett et al*., 2008]. Yet others have sought to understand the relationships between cities and climate change. For instance, while *Dawson* [2007] suggests a framework for analyzing urban systems with evidence-based tools to help engineers and urban planners design effective policies, *Bulkeley* [2013] builds on socio-technical transition theories to develop a framework with which to understand the dynamics of urban climate governance. Few of these, however, study the links between urban areas and carbon emissions resulting from transboundary water and energy infrastructures [*Ramaswami et al*., 2012], or view urban areas and their socioeconomic processes through an ecosystems lens to model urban carbon fluxes [*Churkina*, 2008].

Many of these frameworks have a disciplinary emphasis [e.g., *Bulkeley*, 2013], or are largely focused on modeling [e.g., *Churkina*, 2008] or more accurately describing particular urban systems [*Ramaswami et al.*, 2012]. While some of these incorporate socio-institutional dimensions [*Grimm et al*., 2008], many often depict these as inputs to scenario development, or as external drivers or constraints on a physical system. The novelty of our framework rests on the integration of three broad research domains, and incorporation of diverse motivations, research questions, terms, definitions, and methods (Table 1). We propose to apply this integrated framework, depicted in Figure 1, to the analysis of

1. Key multiscale interactions between urbanization processes and urban areas as places or social, ecological, and technical systems (i.e., socio-institutional, natural, and built environment systems, respectively) affecting energy and land use;
2. The mechanisms by which the exchange of carbon flows within and outside urban areas affects the atmospheric, terrestrial, and aquatic systems;
3. How carbon feedbacks (e.g., climate change) can impact urbanization; and
4. The mechanisms by which the interactions between urbanization, urban areas, and carbon impose limits and barriers and at the same time open opportunities for interventions aimed at transitioning to low-carbon urban futures.

A focus on the following questions through the lens of our framework will help define research concepts and methods, produce interconnected results, and close knowledge gaps as a step to move us toward a more integrated research agenda:

i. What do existing disciplinary domains say about the key urbanization processes and attributes of urban areas that drive carbon emissions?
ii. How do the relationships between urbanization processes, urban areas, and carbon vary over space, time, and scale?
iii. What are the major uncertainties associated with questions i and ii?
iv. When and how do urbanization processes, urban energy systems, and carbon emissions "lock-in" such that future emission trajectories are difficult to alter?
v. What are the opportunities for altering urbanization trajectories toward lower carbon pathways?

(i) What do existing disciplinary domains say about the key urbanization processes and attributes of urban areas that drive carbon emissions?

Different strands of scholarship within the social, engineering, and natural sciences have tackled diverse research questions and used different concepts and methods (Table 1) to explore changes in energy usage and carbon emissions. These studies certainly incorporate urbanization but they usually only touch on limited aspects of it (Figure 1). Further, while these studies may offer partial insight into one or two of the three systems found in our framework, i.e., the natural, built environment, and the socio-institutional systems (Figure 1), the dynamic interactions between urbanization and urban areas are mostly left unexamined.

The social sciences, such as demography, sociology, geography, and economics, have engaged with small subsets of the dimensions of urbanization (Table 1) and more recently with the interacting effects of *socio-institutional system* factors on energy and land use and GHG emissions [*Marcotullio et al*., 2014]. One of the most common areas of focus is demographics, i.e., population size, structure, density, and rate of growth. For instance, while aging populations have been shown to cause reductions in consumption patterns and carbon emissions [*Dalton et al*., 2008; *Liddle and Lung*, 2010], the trend toward smaller households, which manifests differently in high-, middle-, and low-income countries [*Bradbury et al*., 2014], means that the number of households has expanded more rapidly than the total population size. This demographic shift increases GHG emissions as economies of scale are reduced and per capita energy consumption and carbon emissions are significantly higher in smaller households [*Liu et al*., 2003; *Pachauri*, 2004; *Pachauri and Jiang*, 2008]. Another common area of focus has been individual-level wealth or affluence, which is typically positively related to energy use and carbon emissions [*Marcotullio et al*., 2014]. However, the economic dynamics of a city and its function within a multilevel system of cities are equally important. For instance, cities where extractive activities and fossil fuel-intensive manufacturing predominate have higher levels of local carbon emissions per capita than mature, service, and financial cities [*Weber and Matthews*, 2008; *Dodman et al*., 2011]. Another focus area has been institutional or governance structures, defined as the policies, rules, culture, markets, and practices shaping how actors such as energy managers, providers, and users interact with carbon and energy use in cities. Economic-growth policies combined with land use and transportation planning affect carbon emissions by defining patterns of human settlement and economic development [*Marcotullio et al*., 2014]. Three other factors have also been studied as they affect carbon emissions: energy prices and energy services provided by public or private utilities; the technologies of power generation, system control, and energy use; and environmental policies, particularly climate change policies, as they influence energy efficiency, carbon intensity, and new market niches for “green” energy industries [*Monstadt*, 2009].

Motivated by identifying options to decouple urbanization from its energy and carbon impacts, engineers and industrial ecologists have designed metabolism and life-cycle analyses to quantify the energy and material inputs (electricity and fossil fuels) and GHG emissions of components of the *built environment* (*or technological*) *system* such as the construction, operation, and end-of-life management of transportation, building, water, energy generation, and waste [*Pincetl et al*., 2014]. They have analyzed the quality of life implications of increasing reliance on remote material and energy supply [*Chester et al*., 2014]. Engineers have focused on the carbon content of the energy sources that cities use. For example, urban areas that are able to draw on nearby sources of hydroelectricity (such as Stockholm, Seattle, Rio de Janeiro, and São Paulo) or natural gas (London) will emit a smaller volume of carbon for a given amount of energy than cities that rely on coal for energy [e.g., Washington, DC, Chinese, and South African cities; *Kennedy et al*., 2011; *Brown et al.*, 2008]. They have also explored how factors such as high construction and upgrade costs, increasing returns, legal constraints, and the long lifespan of infrastructures make them prone to lock-in (question iv). They have found, for instance, that in 2006 the production of two infrastructure materials, steel and cement, contributed between 7% and 9% of carbon emissions globally [*Seto et al*., 2014]. However, a lack of consistent data collection makes it difficult to explore how varying urbanization processes result in the development of different urban infrastructures, urban forms, and related energy use and carbon emissions.

Natural scientists have focused on quantifying carbon fluxes and pools (Table 1) and key carbon-relevant attributes of *natural or ecological systems*. They have studied the natural milieu, i.e., the location and natural physical features of any given urban area, as it affects land uses and energy demands for heating and cooling and, thus, carbon emissions [*Wilbanks et al*., 2007]. They have investigated carbon-cycle processes [*Pouyat et al*., 2006; *Townsend-Small and Czimczik*, 2010; *Zhang et al*., 2013], pools [*Churkina et al*., 2010], and how they are altered by urbanization [*Kaye et al*., 2006, 2008; *Churkina*, 2008]. Natural scientists have also examined carbon flows emanating within and from cities [*Pataki et al*., 2006] and the ability of local and hinterland atmospheric, terrestrial, and aquatic pools to assimilate vast amounts of carbon flows [*Hutyra et al*., 2014]. Lastly, natural scientists have quantified the influence of air sheds, and urban terrestrial and aquatic ecosystems (each with associated carbon pools) on carbon emissions or flows from urban areas through natural processes of carbon fixation or respiration [*Hutyra et al*., 2014], a capacity that relates to the dynamics of the *carbon cycle* (Figure 1).

All these research efforts have advanced knowledge on key pieces of this intriguing puzzle and resulted in a detailed understanding of some of the processes and components in our framework (Figure 1). However, there have been very few empirical or theoretical attempts to develop coproduced, interdisciplinary, and integrative approaches that combine all these insights into a richer understanding and quantification of how different levels and interactions of the processes and systems of urbanization and urban areas may affect changes in land use and in the sources of energy, energy demand, energy use intensity, and thus spatial and temporal patterns of GHG emissions differentially over time and space.

(ii) How do the relationships between urbanization processes, urban areas, and carbon vary over space, time, and scale?

Beyond a static or place-based understanding of the relationship between urbanization, urban areas, and carbon, different strands of scholarship have shed light on key spatial and temporal variations. First, historically high-income countries have experienced exponential increases in energy use and carbon emissions related to an urban transition (shift from predominantly rural to increasingly urbanized nations) and an energy transition (shift in the quantity, quality, and carbon content of energy), together with modest increases in population growth. That has not been the case with low- and middle-income countries, which had registered a nearly exponential increase in population, an array of pathways of urbanization, industrialization, and thus, different (though, still frequently linear), increases in energy use and carbon emissions [*Grubler*, 2008]. In other words, most of the growth in energy use and carbon emissions in high-income countries (and certainly among wealthier populations globally) has resulted from affluence-related increases in per capita consumption, whereas for low- and middle-income countries [and for poor populations globally; *Dodman*, 2011], most of the relatively lower pace of growth in energy use and carbon emissions historically has been driven by increases in population. This is illustrated by the fact that the per capita emissions embodied in infrastructures of developed countries (53 ± 6 Mg CO_2) are five times larger than in developing countries (10 ± 1 Mg CO_2) [*Seto et al.*, 2014].

This trend has changed in recent decades. The urban and energy transitions are shifting to Asia and Africa, where many low- and middle-income countries are located [*Montgomery et al.*, 2008; *UN-Habitat*, 2011]. While the populations of some cities in high-income countries are stabilizing, the proportion of the world's population in Africa and Asia is growing rapidly, with the bulk of this growth taking place in smaller urban areas. While this adds a carbon challenge to the often weak institutional mitigation capacity small and medium cities have, it offers a mitigation window of opportunity. [*Romero Lankao and Dodman*, 2011; *UN-Habitat*, 2011; *Seto et al.*, 2014]. Because most of the urban development in these areas has yet to occur, and assuming key urban decision makers have the necessary will and institutional capacity, their ability to move to low-carbon futures could be redirected through strategic development initiatives, such as renewable energy systems, and effective spatial and transportation planning. As for regional differences in future urbanization trajectories, large uncertainties remain which will be explored in detail in question iii.

The second trend is the expansion of urban land areas and a worldwide and long-term decline in urban population densities, both of which also vary across and within countries and urban areas based on historic trajectories that cannot be changed so easily (path dependency). For instance, while the average density of cities in high-income countries declined from 3545 people/km^2 in 1990 to 2835 people/km^2 in 2000, in lower-income countries the average urban population density in cities declined from 9560 people/km^2 in 1990 to 8050 people/km^2 in 2000 [*Angel et al.*, 2005]. This trend of reduced urban densities is projected to continue into the future as a result of cities shifting from monocentric to polycentric patterns of development [*Aguilar et al.*, 2006; *Bertaud et al.*, 2011]. In *monocentric* patterns represented by New York, London, Mumbai, and Singapore, most economic activities, jobs, and amenities are concentrated in the central business district (CBD) and public transit (a lower carbon option) is the most convenient transport mode. In *polycentric* patterns, exemplified by Houston, Atlanta, and Rio de Janeiro, jobs and amenities are located in multiple centers and most trips are from one district to another. Mass transit is difficult and expensive to operate, and single-person vehicles or collective taxis are the more convenient (but higher carbon) transportation options for users. These changes mean that key features of urban form such as density, land use mix, and connectivity [*Seto et al.*, 2014] also vary across and within countries in nuanced ways.

Of equal importance are intraurban differences in energy and land use resulting not only from the social and ecological diversity characteristics of urban areas [*Marcotullio et al.*, 2014], but also from the endless array of sectors, infrastructure, and processes involved in urban energy and land uses, and thus in GHG emissions [*Hutyra et al.*, 2014]. Accounting for these differences could shed light on intraurban and regional inequalities and thus on differential carbon mitigation responsibilities.

These trends manifest in context-specific ways across and within urban areas and over time. However, the context- or typology-specific changes that underlie urban scaling are unexplored; whether this set applies to different urban areas in different parts of the world and in different points in time is also unknown. For example, development within areas of China, India, and Sub-Saharan Africa, each with unique dynamics, may or may not follow models developed for Europe or the United States [e.g., *Parnell and Walawege*, 2011; *Seto et al.*, 2012b]. Particularly unexplored are the carbon implications of urban transitions aided by import-substitution industrialization, as occurred in Latin America, which resulted in industrialization processes that were unable to absorb the growing labor force, and left urban authorities with no means to provide universal access to public transportation, which had important energy implications [*Romero-Lankao*, 2007]. Another challenge lies in understanding how these compare with countries such as those in Sub-Saharan Africa, where urbanization and industrialization have largely proceeded independently [*Parnell and Walawege*, 2011].

The complexity of factors accounting for differences in urbanization, urban areas, and carbon over time and across space suggests the need to account for variations among the world's cities within all three of our analytic systems as well as context. It means that low-carbon solutions will not be "one size fits all." Developing an appropriate typology that incorporates key components of urban socio-institutional, built environment, and natural systems and urbanization patterns globally, coupled to models and scenarios of carbon sources and sinks—indeed, the entire carbon balance—is a potential way forward for studies of urbanization, urban areas, and the carbon cycle.

(iii) What are the major uncertainties associated with questions i and ii?

Three major uncertainties exist in our understanding of the drivers of urban carbon emissions globally. Existing efforts to explore future urbanization and carbon dynamics do not account for variations in the levels of development, urbanization, and urban transitions across and within countries, let alone within urban areas. Some cities in high-income countries are stabilizing, while others in rapidly growing countries follow different development trajectories. For instance, *O'Neill et al*. [2012] project that by 2050, urbanization levels could be between 38% and 69% in India and between 55% and 78% in China. Note that this does not account for the quite different nature of urbanization in these two countries. Second, the range of projected increases in land use during 2000–2030 is large and does not take into account of changes in built environments and infrastructures [*Seto et al*., 2014]. However, these models can be used as a first step to estimate the carbon implications of infrastructure developments. The third uncertainty relates to the lack of data on both stocks and fluxes and an unexplored component of the "missing sink," which may be in aggrading forests, particularly in the Northern Hemisphere. Estimates of energy-related CO_2 emissions are roughly equivalent to nearly half of the current global uptake by the oceans and terrestrial biosphere, but are notoriously uncertain components of the global carbon budget [*Le Quéré et al*., 2009]. These issues underscore the importance of a more careful refinement of measurement and estimation of urbanization processes, emission rates, as well as controls and leverage points associated with urban areas.

The study of "tipping points" and nonlinearity in the context of the interactions of urbanization with the carbon cycle and the climate system can provide information regarding the necessary and sufficient conditions for moving to alternate urbanization trajectories. Research in this area should focus not only on whether and when urbanization and urban systems may experience transformations and interact with the carbon cycle, but also on relevant uncertainties, a point we will discuss in section 3. This includes points at which changes to the carbon cycle create feedback loops to influence the urbanization process itself (Figure 1).

In summary, in order to develop a fuller understanding of current and future links between urbanization, cities, and the carbon cycle, it is important to recognize and quantify uncertainties. There are uncertainties inherent in each of the parameters of the conceptual model (the urbanization processes, their interactions with socio-institutional, natural, and built environment systems, how these impact the carbon, and how carbon cycle feedbacks can impact urbanization; Figure 1). Furthermore, there are uncertainties in how urbanization processes and associated carbon emissions will evolve in the future. This means that uncertainties about urbanization and cities may be of similar magnitude to uncertainties in other components of the global carbon cycle (and climate system), and therefore, highly sensitive to policy development based on an expansion of knowledge in this area. Finally, our framework itself must develop continuously, based on any new coproduced knowledge gained in the process of studying the parameters and their interactions.

(iv) When and how do urbanization processes, urban energy systems, and carbon emissions "lock-in" such that future emission trajectories are difficult to alter?

While we know that the patterns of energy and land use and carbon cycle alterations we currently observe in and by cities are almost certainly unsustainable, we know little about the conditions under which we may expect to see cities reduce their reliance on carbon and move from a high-carbon trajectory to a low-carbon trajectory. *Socio-technical transitions theory* (STT) and *political ecology* have developed frameworks to explore the influence of actors such as energy providers and users and the socio-institutional factors affecting their practices on the development pathways of urban energy systems [also called energy regimes; *Romero-Lankao and Gnatz*, 2013]. STT focuses on long-term, multidimensional, and fundamental transformation processes through which established energy or transportation systems shift to different modes of resource use and new relationships with the environment [*Geels*, 2002, 2011]. Political ecology approaches underscore the fact that power relations among actors with different values, perceptions, interests, and assets are at the core of facilitating or restricting socio-environmental conditions for the emergence of change [*Heynen et al*., 2006; *Lawhon and Murphy*, 2012].

A transition entails far-reaching changes along the urban built environment, socio-institutional, and natural systems and urbanization processes. It includes a broad range of actors and unfolds over long time periods. Transitions result from the dynamic interplay of niches, regimes, and landscapes [*Geels*, 2002, 2011]. The *landscape* is the broader and more stable level made of national and global economic developments (e.g., road infrastructure systems) and normative values (e.g., freedom and individuality) that broadly shape energy trajectories, e.g., of personal transportation. The *niche* is the least stable level, where energy innovation and learning occur (e.g., first internal combustion engines that substituted the steam-engine automobiles). A *socio-technical regime* organizes the activities and relationships among urban actors such as energy or transportation providers and users, whose practices and shared understandings of priorities and appropriate actions (e.g., individual mobility), and technologies are intertwined with institutional structures (land and transportation planning and traffic rules). An energy or transportation regime is "dynamically stable" and imposes a logic and direction for incremental change along established pathways of development or path dependency [*Liebowitz and Margolis*, 1995]. Path dependency is an outcome—such as the power systems used to supply urban energy [*Brown et al*., 2008]—that exhibits dependency on initial conditions such as availability of energy sources (e.g., coal versus hydroelectricity), climatic conditions, and socio-institutional factors that in turn are perpetuated by prior actions (growth policies, regulation, energy prices, and taxation structures) leading to infrastructures, infrastructure design life, technologies, and practices that are difficult and costly to change. Lock-in also happens through infrastructure development [*Reyna and Chester*, 2014].

Despite a regime's dynamic stability, characteristics of its landscape and the occurrence of niches and innovations can lead to its destabilization and the emergence of new states that may ultimately become new regimes. For instance, forms of low-carbon urban innovations in energy have been identified around socio-technical networks [*Bulkeley et al*., 2012], which appear to be linked with particular vested interests and specific contexts of urbanization (path dependencies). Two other sources of change have been explored by political ecology scholars: conflict and contestation of environmental decisions around access to, use of, or redistribution of energy or land, with resulting environmental or livelihood implications; and exogenous triggers, such as resource depletion pressures, climate risks, and changes in risk tolerance resulting from shifts in economic and or political dynamics [*Romero-Lankao and Gnatz*, 2013].

A research agenda focused on the relationship between urbanization, urban areas, and carbon can draw on STT and political ecology to account for how, when, and why urban energy regimes change, and for scientists and practitioners to identify opportunities and barriers to intentionally changing this relationship to encourage low-carbon trajectories. We have identified a series of issues that, if answered, would make significant progress toward these goals.

A change in the relationship between urbanization, urban areas, and carbon can be hindered, intentionally or unintentionally, by the continued investments in technologies, infrastructures, and policies that are associated with fossil fuels and their related carbon emissions [see also *Chester et al*., 2014]. To determine the extent to which change is possible, it is first necessary to know to what extent cities have created limits and path dependences through their investments in physical infrastructure, political institutions, and public policies that are likely to result in a continued reliance on fossil fuels or sprawled urban growth and thus in high-carbon futures. Answering this question requires that scientists and stakeholders critically evaluate the sources and strengths of path dependencies (e.g., our reliance on fossil fuels) as they relate to energy and carbon. If change is incremental, along established pathways of urban development and carbon interactions, where do path dependencies exist and what are their sources? Do these investments act to define carbon-intensive energy use in some places? And how is the current carbon dependency of specific cities coproduced by existing conditions and investments (e.g., in private-vehicle transportation infrastructure)? Is path dependency more relevant in mature cities or in cities from high-income countries? To answer these questions, an integrated understanding of the relationship between factors such as growth policies, political decision making and incentives, infrastructure operation, and carbon intensity is required.

While we know that there are likely to be significant barriers and limits to transitioning cities to a low-carbon trajectory [*Brown et al*., 2008], a scientific and coproduced understanding is needed of the ways in which the built environment, socio-institutional, and natural systems and urbanization processes, and their interactions, act as constraints to changing the relationship between urban areas and carbon. How does the significance of each of these barriers vary across and within cities and over time? Are there commonalities across cities and time periods in how these barriers arise and are reinforced? Interventions at different scales (e.g., individuals, communities, markets, and nations) may also encounter different barriers. New methods and data able to attribute causality for change or lack of change, and to identify and account for both the commonalities and differences between cities, are needed.

(v) What are the opportunities for altering urbanization trajectories toward lower carbon pathways?

Research must not only explore limits and barriers, however, it must also seek an understanding of how opportunities to transition to sustainable urbanization pathways emerge. Important areas for research revolve around an improved understanding of the opportunities for change toward low-carbon cities, and have been explored by different strands of social science scholarship. Some scholars engage with the range of multilevel spatial planning measures of relevance for reducing carbon emissions [*Seto et al*., 2014], whereas others study the role of governance and governmental policies in fostering transitions through, so-called, transition management cycles [*Loorbach and Rotmans*, 2010; *Park et al*., 2013]. Still others have researched the roles played by multiple governmental, private, and community actors with various purposes [*Castán Broto & Bulkeley*, 2012] and suggest that interventions to alter urbanization pathways need to consider the divergent claims and values at play.

Research on opportunities for change has thus been dominated by the social sciences and needs to be better integrated with engineering and natural sciences in codesigned and coproduced ways. How can these different insights be integrated with contributions from natural sciences and engineering to explore the optimal intervention points, or opportunities, for transitioning the socio-institutional, technologies, and built environments of cities to change their relationships with the natural systems that support them and foster low-carbon trajectories? We know that the timing of interventions can influence their costs and benefits. For example, infrastructure retrofitting is often more costly than incorporating innovative design elements at the beginning of a project, but these interventions may also ultimately be less carbon intensive than deploying new infrastructure [*Chester et al*., 2014].

At what stage of various urbanization processes will interventions be most effective based on a number of evaluation criteria, including efficiency, effectiveness, and equity? Existing decision-making structures, at multiple scales, may provide opportunities for intervention at different points in time. For example, many cities go through strategic planning processes every 5 or 10 years, but changes such as the replacement of old infrastructure, or urban renewal, or informal settlement upgrades may have different cycles. We need a better understanding of the opportunities for intervention that exist within existing economic-growth policies and decision-making frameworks, including informal ones of relevance in many cities, and the extent to which these align with proposed intervention options for low-carbon trajectories. Further, low-carbon interventions have the potential to produce cobenefits and additional opportunities to actors and sectors outside the immediate scope of a particular project [*UN-Habitat*, 2011]. For example, infrastructure investments that reduce carbon emissions can also contribute to the overall economic growth of a city, and reducing the emissions of power plants can have health benefits [*Harlan and Ruddell*, 2011] and reduce urban populations' vulnerabilities to a changing climate [*Romero-Lankao and Qin*, 2011]. In order to fully understand the source and scale of intervention opportunities, we must also identify the extent to which there are cobenefits from low-carbon transitions, who is likely to experience these cobenefits, and to what extent the costs, benefits, and cobenefits of implementing measures are equitably distributed. There are political, financial, and environmental trade-offs, between the various options for the distribution of benefits, and these trade-offs also need to be understood. Crisis, conflict, and innovation both within and outside of cities can also lead to new technological and social configurations.

Finally, how do we create new, coproduced knowledge for overcoming barriers to change? In many ways making progress in this area will require that we thoroughly mine past experience as we think about the future. While STT and political ecology have shed light on how and why large and rapid transitions have occurred in the past, the rate at which urbanization and urban areas are transforming the carbon cycle requires a different and more integrated understanding at the scale at which transitions may begin in the future. Toward this end, we must identify new and prototypic case studies and common patterns of change with the explicit intention of understanding low-carbon transitions. It is also necessary but not sufficient to collate and evaluate our experiences with the low-carbon interventions of the past, to develop a more general understanding of how barriers are overcome. Through this exploration we may discover the necessary conditions for different policy interventions, such as congestion fees or commuting programs, and what successful financing strategies have been used. We can also begin to see why different types of infrastructure solutions performed well or poorly in different types of cities, what strategies successful urban actors use to initiate change in their cities, and who makes the decisions about how inclusive that change will be. Ultimately, developing both a specific knowledge bounded by time and space will lead to a more global understanding of how barriers to change are overcome by cities. This knowledge will be critical to the creation of low-carbon transitions.

3. Toward an Integrated Understanding of Urban Area Carbon Flows: A Critical Knowledge Pathway to Low-Carbon, Sustainable Futures

Recent years have witnessed a number of research efforts that have considerably advanced our understanding of the attributes and multidimensional links between urbanization processes, urban areas, and carbon. These studies have also shown us some of the barriers and opportunities to creating low-carbon, sustainable futures. Natural scientists have gained a more detailed understanding of carbon flows and of attribution of sources for some cities. While social scientists have explored the urbanization processes driving changes in socio-institutional systems, engineers have quantified carbon-relevant energy and material inputs and outputs of different infrastructures and services of the built environment system. Scholarship has also shed light on fundamental spatial and temporal variations in the relationship between urbanization, urban areas, and carbon. Furthermore, social scientists have analyzed some key triggers, drivers, and limits to low-carbon emission, urban transitions.

Even considering their great advances, however, these studies are faced with multiple challenges and limitations. Some of these limitations are related to the geographic and temporal scope of existing efforts resulting from ad hoc studies driven by individual scientists' interests and preferences rather than by a scientifically sound and socially relevant case-study selection strategy. Others have resulted from differences in framing, scope, and definition, creating challenges with compatibility and comparability of data and findings.

A series of actions that build on both the thematic papers and this synthesis paper are suggested in order to move beyond these limitations and combine a plethora of scattered and discontinuous insights to arrive at integrated understandings of how the interaction of system components in urban areas, and in the process of urbanization, may affect changes in energy and land use. Research on the differences in these interactions may not only form the basis for an understanding of differential spatial and temporal patterns of carbon emissions over time and within and across cities but may also inform planned interventions and assessments of the effectiveness of those interventions at the city level. To achieve this knowledge, an interdisciplinary coproduced research approach, combining insights from the natural and social sciences and engineering must examine:

1. The multiple dimensions of recent urbanization processes and alternative urbanization futures: While scholars have explored some of the social processes of urbanization (e.g., population dynamics and affluence), robust theories, methods, and data are needed not only to conceptualize and measure the more holistic concept of urbanization but also to understand the relative weights of the diverse features of urban systems on energy and land use and, thus, on GHG emissions [*Marcotullio et al*., 2014]. Furthermore, novel methods and data are needed to attribute causality for change or lack of change, and to identify and account for both the commonalities and differences between and within cities.

2. Two key infrastructure or infrastructural interactions or couplings [*Chester et al*., 2014], the first of which relates to how existing or planned infrastructures may more effectively reduce carbon emissions, while being resilient to heat waves, floods, and other stressors climate change is projected to increase. Secondly, as there is an interdependence between socio-institutional\informational factors and water, energy and land use, transportation and building form, materials and structure, research is needed that explores the interactions between infrastructures (e.g., energy-efficient buildings), informational systems, regulations, and individual preferences (e.g., for bigger houses).
3. The fundamental, yet insufficiently understood, carbon flows occurring differentially within and across different urban areas [*Hutyra et al*., 2014], namely land-atmosphere carbon exchange processes resulting from land use changes; land- and water-based carbon flows in and around urban areas; and biogenic exchange of carbon in urban vegetation and soils.
4. More robust and complex typologies and modeling in the quantification and attribution of the carbon impacts of cities in low-, middle-, and high-income countries with considerations including: emerging versus mature cities; monocentric versus polycentric cities; cities in differing geographical contexts (e.g., deserts, grasslands, temperate and tropical forests, coasts); cities with different institutional or governance arrangements; and cities with different economic functions (e.g., industrial, services, or recreational/tourism cities).
5. Intraurban variations in energy and land use based on population or neighborhood demographic, socioeconomic, institutional, and infrastructural characteristics that, even within cities, create differential levels of responsibility for changes to the carbon cycle.

An integrated understanding of the processes of urbanization and the impacts of urban areas on carbon flows can more effectively inform and guide the creation of infrastructure and research programs that will support coordinated, long-duration data collection for urban areas across the world. Data collected should include climactic and biophysical observations along with a wide range of the features and carbon impacts of urbanization, including information that has traditionally been segmented within different disciplines. The data will include indicators of

1. Economic growth, population size, structure, and rates of growth;
2. Technologies and technological change;
3. Urban planning and regulations;
4. Infrastructure planning and code specifications;
5. Market instruments, legal mandates, and other governance factors;
6. Political discourses surrounding fossil fuels and land use;
7. Lifestyle choices and carbon-relevant behavior and worldviews;
8. Urban form elements such as density, land use mix, and connectivity; and
9. Carbon elements such as
    a. Carbon embedded in urban infrastructures and built environments,
    b. Carbon in soils,
    c. Carbon sequestered in urban green spaces, and
    d. Carbon emitted to the atmosphere.

Such data collection would lead to a strengthening of the nascent field of modeling and observing urban carbon pools and flows. Spatially and temporally explicit observations of urban carbon stock fluxes will only be effective if efforts are undertaken to discover the linkage between urbanization processes, systems, and their variation over space, time, and scale [*Gurney et al.*, 2012].

Data will need to be collected in a variety of formats and across scales of space and time. These data will help identify and understand the feedbacks between infrastructures, and socio-institutional and natural systems and will get better as it is collected consistently over longer periods and with comparisons of different spatial and socio-ecological contexts. It will also aid in the development and testing of theories of urbanization, urban areas, and their interactions with the carbon cycle.

For such approaches to reduce the uncertainties inherent in each of the parameters of our framework, they need to include an evaluation of the multiple dimensions of recent urbanization processes that informs an exploration of alternative urbanization futures in a way that accounts for variations in the ways societies organize their urban areas spatially, socially, and technologically. Few studies explicitly examine urbanization globally [*Marcotullio et al*., 2014], and more needs to be done to incorporate the carbon impacts of changing causal drivers within the three systems (Figure 1), and to empirically test inferred relationships between energy and land use and elements of urbanization processes such as governance [*Marcotullio et al*., 2014].

We need to fully explore the potential suite of attributes amenable to observation and critical to understanding urban carbon flows in order to improve our observational and modeling frameworks and capacity to monitor, report, and verify urban flows in spatial and temporal detail; and use atmospheric observations to understand how emissions are actualized in the atmosphere [*Gurney et al*., 2012; *Nassar et al*., 2013]. These urban carbon monitoring and modeling efforts will be of utility to urban practitioners who are traditionally focused on specific policies and measures within urban areas or regions. An urban research campaign that combines surface observations, inverse modeling, high-resolution flux estimation, and new remote-sensing technology across an array of urban areas that varied in their urban typology could transform carbon cycle science [*Duren and Miller*, 2012].

Furthermore, by fostering an understanding of the spatiotemporal distribution of emissions, this effort would be a giant leap toward more accurate estimation of changes in the global carbon cycle. A better understanding of intraurban variation is also relevant, because there are often differences in emission levels based on sector, process, and population or neighborhood characteristics that, even within cities, create differential levels of responsibility for changes to the carbon cycle.

Finally, this combination of key scientific domains would be interdisciplinary (i.e., integrating methods and theories from different disciplinary domains to bear on this issue) and it would engage scientists with urban actors and stakeholders in the codesign and coproduction of science [*Hackmann et al*., 2014; *Weaver et al*., 2014]. We build on a broad, three decades long tradition of integrated and coproduced scientific efforts (e.g., Long Term Ecological Research (LTER) Network, Intergovernmental Panel on Climate Change, United States Global Change Research Program, and Future Earth) to suggest the following priority actions:

1. International and national research councils and associations, research funders, and research teams need to ensure that scientifically robust and socially relevant funding opportunities include calls for social scientists, physical scientists, and engineers to work together on an equal basis and with stakeholders to codesign and codevelop research on urbanization, urban areas, and carbon flows.
2. Decision makers at all levels need to appoint social scientists, physical scientists, and engineers to scientific advisory bodies, expert committees, and working groups working on urbanization, urban areas, and carbon (e.g., Global Carbon Project, International Council for Local Environmental Initiatives (ICLEI), World Bank, and mayor national associations and regional scientific centers).

Interdisciplinary science is not an easy endeavor. Significant transaction costs result from differences in mental models, in scope, methods, and definition of terms. Therefore, practical mechanisms need to be put in place [e.g., historical analysis, place-based research, and maps, scenarios, and uncertainty characterization; *Weaver et al*., 2014] to encourage engineers, physical scientists, and social scientists to truly collaborate on an equal basis. The nature of the research and policy challenges related to transitioning to low-carbon urban futures means that “social sciences cannot merely be and add-on to research agenda driven only from the biophysical side (or vice versa)” [*Weaver et al*., 2014, p. 658]. This is equally true for the engineering side of our coproduced research effort. The emphasis here should be on creating a scientific understanding that is greater than the sum of its parts.

4. Closing Remarks

In the wake of political constraints to creating low-carbon futures, urban areas are emerging as climate policy and technology innovators, urbanization process laboratories, fonts of carbon-relevant experiments, hubs for grass-roots mobilization, and centers for civil-society experiments to curb carbon emissions and avoid widespread and irreversible climate impacts. The design of successful interventions, however, will depend on systematic, coordinated, and coproduced research efforts to understand both the multidimensionality of urbanization and the coupled understanding of urban processes and urban areas with energy and land use and carbon flows. Multiple engagement efforts between the research community, urban actors, or stakeholders in the creation and application of low-carbon solutions will also be critical to success.

Both opportunities and significant barriers and limits exist to transitioning cities to low-carbon trajectories. However, the development of an integrated and coproduced scientific understanding could be a critical ingredient in the development of transitional journeys to low-carbon futures and the avoidance of obstacles along the way. For example, interdisciplinary teams and urban actors or stakeholders could engage in science coproduction processes to explicitly analyze, to what extent cities have created constraints and path dependences through investments in physical infrastructure (built environment systems), or through political institutions and public policies favoring growth, individual modes of transportation, low-density settlements and other carbon-intensive activities, and progrowth public policies (socio-institutional systems). This coproduced knowledge could help determine constraints and path dependencies that bias urban systems toward specific carbon-emitting futures, and under what socio-political and changed climatic conditions (e.g., increase in the intensity and/or frequency of heat waves, floods, and extreme weather events affecting energy systems) urbanization trajectories can be shifted toward low-carbon emissions and resilient urban management regimes. It could also inform efforts seeking to coordinate highly fragmented governmental policies or ownership of urban infrastructure and ecosystem services. Perhaps most importantly, it would suggest methods by which this understanding can best reflect the wide variety of physical, environmental, social, and economic conditions across local, regional, and global systems.

For better or for worse, urban areas have become key players in the carbon, energy, and climate arenas because they are both primary sources of emissions and of innovations. Many divergent disciplinary domains have shed light on different components of the relationships between urbanization, urban areas, and carbon. A key challenge for the future is to develop frameworks that coherently integrate these disparate contributions to develop coproduced science that informs more effective policy and decision making. We hope that the four papers in this special issue will lay a foundation for an integrated research agenda by examining the contributions, perspectives, and possible nexus of the domains of social science, engineering, and natural science research in the critical research area of urbanization, urban areas, and the carbon cycle.

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