Sustainable Urban Systems

An Integrated Approach

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Many have recognized the importance of cities in addressing pressing global environmental threats, including climate change, water stress, loss of biodiversity, and resource scarcity (Grimm et al. 2008; UNEP 2012; UN-HABITAT 2011; World Bank 2010). Already more than half the world's people and about 80% of those in developed nations live in cities and urban areas. These vast urban populations consume a majority of the world's resources, contribute to environmental degradation locally, regionally, and globally; and simultaneously are highly vulnerable to the consequent impacts of such changes (e.g., climate change). Developing environmentally sustainable cities is one of society's grand challenges in the coming decades.

Transformation of infrastructure systems is understood to be key to developing sustainable, resource-efficient cities (Boyle et al. 2010; Sahely et al. 2005). The framework for urban green growth developed by the Organisation for Economic Co-operation and Development (OECD) sees infrastructure, along with innovation and human capital, as being the starting conditions for achieving green jobs, green supply and consumption, and urban attractiveness (Hammer et al. 2011). The United Nations Environment Programme (UNEP 2012) identifies five key thematic infrastructure areas for achieving resource efficient cities—building energy efficiency, waste management, sustainable urban transport, water/wastewater, and urban ecosystem management—but stresses that it is integration between sectors and across scales that is most important.

This special issue demonstrates how practical solutions to the development of sustainable cities can be achieved through studying urban metabolism, urban ecology, city carbon and water footprints, the dynamics of city growth, and the interdependency between social actors, institutions, and biophysical system flows.

Our goal with this special issue on sustainable urban systems is to apply methods of industrial ecology toward the sustainable development of cities, their supporting hinterlands, and the networked infrastructure that connects them. The methods include familiar tools of industrial ecology, such as life cycle assessment (LCA), material flow analysis (MFA), environmental footprinting, and scenario modeling; but there is also an effort to push the interdisciplinary boundaries of industrial ecology even further, linking with other disciplines and recognizing that it is social actors (i.e., people) who shape urban systems. Contributions were encouraged from researchers in a broad range of disciplines, including industrial ecologists, urban ecologists, urban planners, architects, geographers, engineers, economists, environmental scientists, planners, political scientists, and sociologists. The articles address fundamental research, development of cross-cutting conceptual frameworks, applied tools (e.g., low-carbon development methods), case studies, and interdisciplinary curricula. Several articles in particular address both the biophysical and human dimensions of sustainable urban systems (Castan Broto et al. 2012; Ramaswami et al. 2012b; Hodson et al. 2012). In introducing this special issue, we begin with interdisciplinary overarching articles on urban infrastructure, metabolism, and environmental footprints of cities in the context of social actors, before moving to more specialized articles on energy and carbon, nutrients, water, and waste.

Metabolism and Footprints of Cities: Shaped by People and Infrastructure

The study of urban metabolism (Kennedy et al. 2007; Wolman 1965)—the stocks and flows of energy and materials in cities and their relationship with urban infrastructure—is central to urban industrial ecology. Many of the articles in this special issue have measures of metabolism at their core, but extend them in various ways. In their article, Kennedy and Hoornweg (2012) make a passionate plea for cities that are serious about sustainable development to conduct metabolism studies.

In a complementary article, Ramaswami and colleagues (2012a) point to emerging research that recognizes that most infrastructure serving cities transcends city boundaries (e.g., energy, water, mobility, waste/wastewater infrastructures). Beyond infrastructures, there is also significant trade of goods and services between cities. To address these transboundary interactions, several cities are going beyond analysis of urban metabolism to develop different types of environmental footprints for cities that integrate in-boundary and transboundary water use, energy use, and greenhouse gases (GHGs) associated with production and consumption activities in cities (Baynes et al. 2011; Ramaswami et al. 2008; Stanton et al. 2012). The

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article describes the different types of footprints emerging from recent research and elucidates their relationships with urban metabolism.

In the context of integrating people (social actors), a review article by Castan Broto and colleagues (2012) compares six different perspectives on urban metabolism. They contrast urban ecology, urban material and energy flows, larger-scale macroeconomic perspectives on production and consumption, and political economy influences on intraurban and urban–rural equity, the latter in the context of social-ecological systems (SES) studies of cities. They argue that a purely biophysical perspective of cities in the context of material and energy flows can downplay the role of people and power politics in shaping urban metabolic flows and the distributional (differential) impact of these flows on people (i.e., on the rich and poor in cities). The authors recognize and make numerous references to water/wastewater infrastructure(s) as they serve different segments of society within cities, but the authors also indicate that many other infrastructures are largely "invisible" in modern cities, often being located outside the city boundary. This review article recommends interdisciplinary integration across urban ecology, urban metabolism, and the politics and governance of urban development, as it can help reimagine a new sustainable development paradigm for cities.

As if in answer to the call of Casta Broto and colleagues, a forum article by Ramaswami and colleagues (2012b) introduces a new social-ecological-infrastructural systems (SEIS) framework that squarely places infrastructures (I) into urban SES, hence SEIS. The SEIS framework is anchored upon the concept of transboundary urban infrastructure footprints that inform both the cross-scale impact of cities on the environment as well as the multiscale risks posed to urban residents by infrastructure–environment interactions. In this framework, three different social actor categories—individual resource users, infrastructure designer-operators, and policy actors—interact with each other, and with infrastructures across spatial scale, to shape multiple urban sustainability outcomes relating to environmental pollution, resource efficiency, public health, economics, risk, and equity. Seven different disciplines—engineering, environmental sciences/climatology, industrial ecology, architecture and planning, behavioral sciences, public affairs, and public health—are integrated in the SEIS to describe how the different social actors, together, shape production, urban design, and consumption pathways toward sustainable city systems.

Wrestling with the balance between urban development and long-term ecological sustainability, a second forum article by Hodson and colleagues (2012) asks how the necessary urban transition will take place, who will lead it, and which social and governance processes will facilitate it. The authors recognize that very different levels of per capita material consumption can result from unique configurations of cities, and that the design of infrastructure networks provides many opportunities for decoupling of economic growth from ecological impacts. Moreover, infrastructure is seen as a sociotechnical system, in which innovations in technical and/or institutional approaches to service provision can help lead to positive development trajectories. They broadly sketch out four types of transitions toward sustainable cities: (1) new urban developments as "integrated eco-urbanism," (2) new urban networked technologies, (3) reconfiguring cities as "systemic urban transitions," and (4) retrofitting existing urban networked infrastructure.

As important as the science (presented in this special issue) is its translation to support the development of effective sustainability policies and programs in cities. A third article (Zborel et al. 2012) explores emerging models for such science-to-policy translation for sustainability at the city-scale compared to the more traditional national-level environmental policy making. The column identifies some of the key challenges as well as the benefits that can arise when researchers and city practitioners work together to develop policies/programs in cities. Best practices for translating research to policy are discussed for individual cities working with colocated research organizations, as well as for multicity organizations that develop protocols and standards for multiple cities at the national and international scale.

The next two sections describe research articles in this special issue that address specific sectors—energy and carbon, and nutrients, water, and waste.

Energy and Carbon

Low-energy and low-carbon cities are intricately linked to the scale of urban activities, type of urban activities, and urban infrastructure, among other aspects (Dhakal 2010; Grubler et al. 2012; Rosenzweig et al. 2011; UN-HABITAT 2011). In the context of industrial ecology, not only are direct energy use and GHG emissions important, but equally important are the indirect energy and emissions embodied in the flow of goods and services to cities. The true nature of a low-energy and low-carbon city cannot be illustrated without considering the transboundary energy and carbon demand embodied in such flows. In this regard, while we have seen past literatures being bridged in recent years, we observe two key limitations. The first is the lack of a reliable accounting of the direct emissions in the cities in developing countries, especially in South Asia, Southeast Asia, and Africa, which is essential for strategies to develop low-energy and low-carbon cities; the second is the existing narrow approach of accounting in cities, which rarely accounts for the energy and emissions embodied in the flows of goods and services without which we cannot convincingly compare cities.

Chavez and colleagues (2012) address both gaps at once with a study of Delhi, India, and accounting for some of the transboundary infrastructure for the city. Clearly it is essential to estimate the energy use and carbon profile of more urban systems, especially in the developing world, and explore avenues to develop low-energy and low-carbon urban systems. When it comes to developed countries, while many urban-scale analyses for energy exist, historical analysis is often lacking. Baynes and Bai's (2012) contribution is very meaningful; it reconstructs the historical energy supply and consumption profile of Melbourne, Australia, and relates the urban development history, its relation to energy consumption, and potential future changes.

In the era of a climate-constrained world, where all future population growth will be in urban areas, cities will be increasingly contributing to global energy use and GHG emissions. The need for transformative changes in urban systems in the long-term while accelerating incremental changes in the very near term are essential. Grubler and colleagues (2012) argue that the potentials for energy-efficient city development are greater from higher-order organizations of urban systems, such as restructuring of urban functions, urban economy, division of labor, urban forms, and basic urban infrastructural setup, which shape the scale and intensity of urban activities. A broader understanding of the urban system is thus essential and policies must address these factors. However, this may not be easy given the way policies are currently made at the local level—policy making is often fragmented, short-term outcome oriented, and often focused on the end of the pipe solutions. In an effort to study the large-scale transformative change possibilities, Reiter and Marique (2012) provide a methodology to model citywide buildings and transport energy use while considering the possible evolution of city energy consumption and the effects of some strategies of urban renewal. Similarly, Mohareb and Kennedy (2012) focus on the temporal dynamics of transformation to low-carbon cities, examining how rates of technical diffusion and building retrofits impact potential future emissions. Meanwhile, Keirstead and Sivakumar (2012) simulate urban energy consumption using an activity-based modeling approach, with an example showing how electricity and natural gas demands in London, England, might be impacted by changes in commuter patterns.

Part of the motivation for transformation to low-carbon cities goes beyond climate change concerns, and is related to some of the cobenefits. This is evident in the article by Susca (2012), which shows how increasing the albedo of New York City, New York, USA, rooftops has both climate change and human health benefits.

Nutrients, Water, and Wastes

Many cities face increasing vulnerability to water stress, for several reasons. Drivers include (1) climate change, which will likely produce hotter, drier, more variable climate regimes in areas of the world that are already hot; (2) rapid growth in the world's urbanized population, and especially in unorganized peri-urban areas; (3) pollution of and/or depletion of groundwater; and (4) increasing per capita water use, paralleling increasing prosperity (Baker, forthcoming). Building resilience is not simply an engineering problem involving more dams and canals. It is a socioeconomic phenomenon that requires a highly interdisciplinary approach, including analysis of governance and social systems, as well as hydrology (Baker, forthcoming; Ramaswami et al. 2012b).

One challenge of studying water vulnerability is that it is inherently a non-steady-state problem—water stress occurs primarily during drought periods (although some cities have managed to cause water stress by overconsumption even during normal hydrologic periods) and during wet periods, which causes flooding. This is very much different from the situation with carbon emissions, which change slowly over time.

A first step in developing useful metrics of urban water resilience is the development of water balances. Agudelo-Vera and colleagues (2012) zero in on the household level to illustrate their "urban harvest approach," which includes minimizing demand, minimizing outputs, and multisourcing. They conclude that demand minimization for houses in both the Netherlands and Australia could reduce water use by more than 40%; furthermore, inclusion of "multisourcing" (mainly rooftop rainwater harvesting) in combination with demand minimization could actually result in net production of water from the Netherlands home. These authors are expanding the spatial extent of the urban harvest approach to include whole cities and other substances. This type of analysis might be very helpful in developing water resilience strategies.

In addition to problems of adequate water supply, urban groundwater and surface water is often polluted. In industrialized countries particularly, pollution from the legacy of combined sewers—sewers that convey both stormwater and sewage—remains a major problem, because treatment plants cannot handle the combined volume. The combined sewer overflow (CSO) often bypasses the wastewater treatment plant, discharging highly polluted water to rivers. Some cities have rebuilt their sewer systems to separate the two types of sewers, and some have built huge underground storage vaults to store the combined sewage, pumping it out after storms to be treated. More recently, some cities have used a distributed "green infrastructure" strategy to reduce the volume of stormwater flows, in part to reduce costs. Sousa and colleagues (2012) use economic input-output life cycle assessment (EIO-LCA) to estimate the long-term carbon dioxide equivalent (CO_2-eq) emissions impact of two "grey" and one "green" CSO mitigation strategies, concluding that the green option had far lower CO_2-eq emissions than either of the grey strategies. This article illustrates the need to link multiple objectives—in this case, water quality improvement with CO_2-eq emissions—to find sustainable solutions to urban environmental problems.

Two articles—by Metson and colleagues (2012a) and by Kalmykova and colleagues (2012)—use material flow analysis (MFA) to quantify fluxes of phosphorus (P) and develop P balances for cities. This research is driven by a growing recognition that phosphate rock supplies may not be sufficient to support human agricultural systems far into the future (Brunner 2010; Cordell et al. 2009), together with a long-standing concern with eutrophication of surface waters. Although our ability to predict "peak production" times is imperfect, the United States had been a net exporter of phosphate rock since the early twentieth century, but has shifted to being a net importer since 1996. Kelly and Matos (2010) give reason to at least be concerned about the sustainability of phosphate supplies and to start thinking about how we might convert cities from essentially once-through systems to circular systems, as Kalmykova and colleagues (2012) note that only 6% of P entering Gothenburg, Sweden, is recycled; very similar to the finding of Baker (2011) for the Minneapolis-St. Paul, Minnesota, USA, urban region. Kalmykova and colleagues quantify potential recycling options for urban P and suggest that cities employ a broader systems perspective for waste management. Metson and colleagues (2012a) examine historical patterns of phosphorus movement in Phoenix, Arizona, USA, expanding on their earlier publication of a phosphorus balance for the region (Metson et al. 2012b).

Going beyond P, there is a substantial need to rethink urban waste streams more generally, both for recovery of various nutrients and for energy recovery. Sometimes these goals might be in conflict: for example, in agricultural regions, the "highest value" of waste food might be for hog feed (especially for the energy content), but diverting food from the waste stream might lower the potential for energy production via incineration of food. Conversely, nitrogen is removed during incineration, lowering the fertilization value of ash. The techniques of industrial ecology are ideally suited for analysis of urban wastes.

The last article to introduce is on wastes of a different kind—specifically electronic wastes (e-wastes). Leigh (2012) notes that an increasing number of U.S. states are passing e-waste laws. She presents a case study of e-waste recycling in the Seattle, Washington, USA, metropolitan area demonstrating the economic benefits of this new sector.

Closing Comments

Overall, this special issue demonstrates how practical solutions to the development of sustainable cities can be achieved through studying urban metabolism, urban ecology, city carbon and water footprints, the dynamics of city growth, and the interdependency between social actors, institutions, and biophysical system flows.

A common theme even in the sector-specific articles is that they address some aspect of the interaction between urban infrastructure either with different sustainability outcomes (e.g., GHG emissions, energy use, water use, human health) or with different agents who shape (for example) energy use in buildings, water use, rates of technological diffusion, resiliency, and other aspects of urban sustainability over time. Thus the overarching theme that emerges from this special issue—and is highlighted in the synthesis/forum articles—is that integration of engineered infrastructures, people, and natural systems is essential for the study of sustainable urban systems. This issue presents a glimpse of such integration via a snapshot of pioneering academic research on sustainable urban systems. Translating such integrative interdisciplinary research to practitioners (such as city staff and elected officials) and nongovernmental organizations will be the next frontier, generating real-world impacts on cities worldwide.

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