



Sustainability in an urbanizing planet

Karen C. Seto^{a,1}, Jay S. Golden^b, Marina Alberti^c, and B. L. Turner II^{d,e}

Sustainability science is use-inspired fundamental research that links knowledge to action such that meeting the needs of society can be balanced with sustaining the life support systems of the planet (1, 2). Nowhere is this action-oriented research needed more than in urban areas that are now home to more than half of the world's population, generating about 80% of the world's economy (3) as well as over 70% of global energy use and global energy-related emissions (4). Depending on the literature and perspectives taken, urbanization and cities will be either key components to the transition to sustainability or major threats to sustainability. The dichotomy in views is partly a result of the wide range in urban conditions and uneven urbanization processes around the world. Urban areas can be sites of innovation and production of knowledge and wealth, and provide widespread access to employment, education, sanitation, and modern energy, but they can also have high levels of pollution, social exclusion, environmental degradation, and cause unintended consequences outside of the urban boundaries; all of these outcomes could occur simultaneously through the same urbanization process.

A number of urban transitions are underway, several of which involve: the change from a predominantly rural and lower-density population to an urban and higher-density living; the shift in economies from agrarian to manufacturing and services, finance, and technology; the increasing resource intensity of energy, materials, and water required to produce a unit of good or service; the lasting imprint and spatial configuration of built environments and their requisite infrastructures; the subtle impact on a broad spectrum of biotic interactions and the significant threats to biodiversity; the increasing complexity and reach of urban institutions and governance to enforce the rule of law and maintain civil society; and the transition from individually demarcated cities and towns to the emergence of mega-urban regions, which are extended metropolitan areas that encompass multiple urban centers and are larger in size than mega-cities.

The simultaneity of these transitions, combined with the scale of mega-urban regions and the expanding

geographic reach of urban processes, signals a significant break in human–environment interactions, from local or regional scale to global consequences. It is important to underscore that these large-scale changes are occurring contemporaneously in hundreds of urban areas around the world, and not just in a few locations. Indeed, what was once considered exceptional—large-scale and rapid urbanization—is now the norm in many places. The scale of mega-urban regions is notable in two key dimensions: (i) the number and concurrent development of them worldwide; and (ii) their physical extent and population size: the Boston–Washington corridor is home to 18% of the United States population; the Pearl River Delta in China has a population of about 120 million; the Tokyo–Yokohama region in Japan covers about 13,500 km², an area larger than Qatar.

Urban populations, economies, and societies cannot be sustained without the support of resources, services, and economies from regional and global hinterlands. The resources on which urban areas rely commonly and increasingly come from places outside of the immediate regions and even countries where they are located. Given the magnitude of current urban transitions and the global reach of their production–consumption systems, there is a need to generate robust scientific knowledge on cross-scale interactions, tipping points, thresholds, and limits that are set off by urbanization to orient urban development toward more sustainable trajectories. This raises critical questions about the relationship between urbanization, especially the emergence of mega-urban regions, and sustainability. How are 21st-century urbanization processes and mega-urban regions altering rural–urban relationships while simultaneously blurring the distinctions between rural and urban? Taken together, how can the aggregate effects of global urbanization help to transition society toward sustainability? Are there successful or effective local sustainability strategies that are transferrable or applicable across the numerous mega-urban regions worldwide?

The starting point for this Special Feature is that large-scale urbanization occurring simultaneously in

^aYale School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511; ^bDepartment of Engineering, East Carolina University, Greenville, NC 27858-4353; ^cDepartment of Urban Design and Planning, University of Washington, Seattle, WA 98105; ^dSchool of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ 85281; and ^eSchool of Sustainability, Arizona State University, Tempe, AZ 85281

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¹To whom correspondence should be addressed. Email: karen.seto@yale.edu.

multiple parts of the world has far-ranging consequences equivalent to or potentially exceeding that of the Industrial Revolution. Rather than attempting to address comprehensively all of the dimensions of urban sustainability, this Special Feature focuses on the emergence of mega-urban changes in structure—be it of land use, infrastructure, or the economy—and their connections to resource use, environmental trade-offs, and human well-being and development. Each paper provides insight into shifts in human–environment interactions and potential challenges, and opportunities for directing these relationships toward more sustainable outcomes. The papers do so through attention to two specific themes that guide the Special Feature: (i) the large scale and rapidity of the growth of urban regions, and (ii) the ensuing environmental consequences of large-scale and simultaneous urbanization. These themes, in the context of the emerging patterns of agglomeration, provide insights about long-term, large-scale urban sustainability.

Key Common Themes

The studies in this Special Feature highlight a number of themes. That urban sustainability is inherently multidimensional and multiscale is one common theme. Solutions at one spatial scale or along one dimension (e.g., energy, land use) may not have the same effect at a different spatial scale or dimension. One example of this is the spatial pattern of urban land use, which results in varying trade-offs at different scales. Locally, compact urban development may save prime agricultural land from conversion (5) and reduce building and transportation energy demand (6), but regardless of the spatial pattern, globally, high levels of urban land-cover change show high rates of phenotypic change in species (7). Taken together, these observations suggest that there is no single optimal urban form, but rather that some desired outcomes may come at the expense of others, and that we need to better understand the trade-offs between multiple, perhaps competing environmental and socioeconomic outcomes.

A second theme explored is that the effects of urbanization may be both significant and observable only when they are examined on aggregate, and focusing only on effects and conditions locally may obscure their cumulative impact at global scales. For example, one of the most transformative effects of urbanization is species alteration (7). The rate of species evolution globally as a result of urbanization could affect ecosystem functions, such as food production and carbon sequestration, with enormous consequences for human well-being. As another example, the effects of urban form are often considered locally, such as on economic productivity and transport energy use. Worldwide urban density, however, could affect building energy use globally as much as technological improvements in energy efficiency (6). Similarly, much evidence from local case studies indicates that urban expansion commonly results in the loss of agricultural land. The first global assessment of future agricultural land loss (5) shows that about 80% of the global cropland loss will take place in Asia and Africa, and that the loss will be acute in a few countries that could potentially lose up to one-third of total crop production. These observations suggest urban sustainability must be achieved at the global scale, raising a number of questions about scale: Are there fundamental urban characteristics that scale or converge with environmental outcomes and performance measures? How do urban–environment relationships vary across scale and how do regional conditions, such as climate or species, respond to and coevolve with large-scale urban change?

A third common theme is the need for quantitative measures of urban sustainability that take into consideration both social and ecological processes. As Sampson (8) points out, the urban sustainability literature is dominated by a focus on environmental dimensions and outcomes more so than societal ones. Social well-being not only plays a profound role in the cultural ecology of a place, it is critical to the vitality and sustainability of urban areas. Inequalities within and between cities have existed throughout history, but there has been minimal work that empirically measures the distributional aspects of equity and well-being in today's cities. To make measurable progress toward urban sustainability, we need to develop new tools and methods that track multidimensional urban inequalities—including both social and ecological processes—at the neighborhood scale (8). Brelsford et al. (9) construct a novel metric that does precisely this, providing a quantitative assessment of sustainable development. Their simple index is a first step toward systematically measuring progress toward achieving development priorities.

Knowledge Gaps

Collectively, the papers in the Special Feature point to a few key knowledge gaps and research priorities. First, more integrative research is needed. We sought research for this Special Feature that crossed multiple disciplinary domains. We readily found urban sustainability work that fits within “the four branches” of sustainability research: (i) biological (e.g., ecosystem services), (ii) social-economic (e.g., well-being, wealth, health), (iii) geophysical (e.g., climate change), or (iv) technical (infrastructure/design) (10). There were many individual case studies of the biological impacts of urbanization, or the health impacts of urbanization, but very little that was integrative across the different branches and that incorporated trade-offs or feedbacks. The articles in this Special Feature illustrate this point: each deals with one aspect of sustainability, such as biological (7), socioeconomic (8, 9), biophysical (5), or technical (6). Each article acknowledges the need to create bridges among these fields and to examine urban and environmental systems as fully coupled or explicitly incorporating feedback loops. As Sampson (8) argues, social and environmental sustainability are strongly connected, and social sustainability may be more fundamental than environmental sustainability for producing livable and equitable cities that can be maintained over the long term. This observation, however, needs to be tested with more integrative research.

Second, there is little comparative empirical work on urban sustainability. Although there are many quantitative studies for individual places, cross-comparative empirical work on sustainability crossing typologies of urban areas and across different geographic regions is sparse. The sustainable development index proposed by Brelsford et al. (9) makes an important step toward providing a simple and intuitive measure of progress toward the sustainable development goals. The increase in urban data and urban analytics appears to have resulted in more fine-detail studies rather than cross-regional comparisons. Improvements in the spatial and temporal resolution of Earth observation data, real-time environmental monitoring, and the availability of user-contributed and social media data should create new ground for more comparative studies.

Third, the urban research and practitioner communities are also in need of more solutions-oriented, fundamental science that is both place-based and spans multiple geographic and administrative scales. What is the nature of the relationships between urban areas and the environment? What controls their dynamic interactions and how can urban development be guided toward more sustainable pathways? Much of urban sustainability research

is conducted at either local or planetary scales, but what policies might international or regional institutions undertake, for example, to reduce unintended consequences in hinterlands or leakage in nonurban areas? How can we use emerging technologies and data sources to test hypotheses about how to overcome urban inequality within cities (e.g., ref. 8)? Several of the articles provide fine-grain data for a few cities (8, 9), but assessments of the feedbacks and trade-offs across spatial scales are required as well.

Fourth, there is need for more theoretically grounded work building toward general explanations of our observations, potentially improving analytical options for projections of future outcomes (8, 9). At least two theoretical pathways warrant attention. The first builds upon and expands extant theory. The majority of this theory applied to urban sustainability is typically drawn from disciplinary foci and involves some component of either the human or environmental subsystem and controlling for or failing to account for the other. Explicit exploration of such theory to components of the other subsystem promises to provide insights that would facilitate the development of more comprehensive understanding required for the second pathway. The latter and more difficult pathway, inferred in coupled social–environmental (also known as coupled human–environmental) systems research framings, involves “true” integrated explanation in which the interactions of the social and environmental urban systems are addressed as fully as possible. This proves difficult because of the complexity of multiple interacting components and the processes affecting them that lead to nonlinear and emergent outcomes. In either pathway, conciliation between systems theory common to the environmental sciences and middle-range theory common to the social sciences is required.

Research Priorities

In aggregate, the articles presented in this Special Feature point to three principle areas of research that need to be resolved in order for society to transition to sustainability.

First, a research priority entails undertaking new integrated studies that aim to “close the loops”: fully connect the socioeconomic and environmental systems and understand their dynamic interplay and feedback (Fig. 1) (11). This new generation of studies requires a new level of collaboration between scientists of multiple disciplines across the natural, social, and data sciences to generate new questions, devise integrated methodologies, and contribute to the knowledge gap in theory. It also demands a more inclusive approach to scientific inquiry that directly reflects the diversity of world regions, societies, and actors.

The second research priority addresses the spatial scale mismatch between human and natural systems that characterize urbanizing regions and the trade-offs of social and environmental outcomes within and across scales (Fig. 1). New research should explicitly target a refined understanding of both the trade-offs and synergies across socioeconomic and environmental functions and the relationships of sustainability across spatial scales, from local to planetary scales. This also requires developments of new theory that concurrently examines trade-offs across multiple objectives. What may be considered to be sustainable locally may not scale to

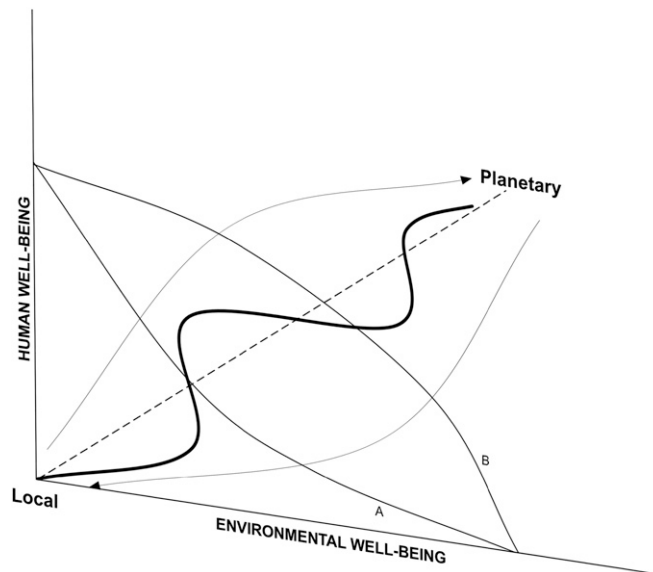


Fig. 1. Conceptual framework of research gaps and priorities for urban sustainability research. The two arcing arrows represent feedbacks and linkages between local and planetary-scale action and impacts. Urban sustainability solutions will affect human and environmental well-being differently at different scales. The nature and function of the relationship between human and environmental well-being to achieve urban sustainability have not been resolved. Thus, the convex (A) and concave (B) curves represent two hypothetical relationships and trade-offs between human and environmental well-being to achieve urban sustainability at different spatial scales. They have different functional forms because there are different relationships at different scales. The intersection of the sinusoid line with each of these curves represents the better sustainability solution at that scale. The thick sinuous line is an illustrative pathway of achieving different targets across different spatial scales.

planetary levels. Moreover, the trade-offs and relationships at one scale may not hold across scales (Fig. 1).

Finally, we need to examine multiple dimensions of urban sustainability simultaneously with new urban metrics to generate quantitative assessments of progress toward sustainable urban development (Fig. 1). This implies both the need to identify new indicators and metrics that more effectively represent the multidimensionality of coupled human–environmental systems and systematically apply them across multiple urban regions. It also entails developing new capacity to take advantage of the highly disaggregated and rapidly expanding availability of data and analytics to transform our understanding of how cities, towns, and urban regions evolve, operate, and innovate.

Contemporary urbanization marks another “Great Transformation” (12). Given multiple global change trends, there is an urgent need to accelerate the transition to sustainability. Urbanization presents a unique opportunity to make this transition while coupling social, economic, human development. The challenge is whether science can deliver.

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