Meta-principles for developing smart, sustainable, and healthy cities

Article *in* Science · May 2016

DOI: 10.1126/science.aaf7160

5 authors, including:

Armistead G. Russell
Georgia Institute of Technology

Rahul Sharma Karnamadakala
University of California, Santa Barbara

as natural, such efforts can shape attitudes toward the environment (Fig. 2). People in increasingly large and dense urban areas may have few or no contacts with the natural world in everyday life. Environmental generational amnesia refers to the psychological process whereby each generation constructs a conception of what is environmentally normal based on the natural world encountered in childhood (*13*). A problem arises insofar as the amount of environmental degradation increases across generations, but each generation tends to take that degraded condition as the nondegraded condition: the normal experience. This helps to explain inaction on environmental problems; people do not feel the urgency or magnitude of problems because the experiential baseline has shifted. Providing opportunities for people to experience more robust, healthy, and even wilder forms of nature in cities offers an important solution to this collective loss of memory and can counter the shifting baseline (*14*). Such opportunities include, for example, large green spaces and parks, rivers restored to some former free-flowing condition, expansive views over water and land, and extensive connective pathways for walking and biking.

Thus, cities designed well, with nature in mind and at hand, can be understood as natural, supportive of both ecosystem integrity and public health. Further psychological studies can describe how specific improvements in available opportunities for nature experience come to affect mental health and environmental attitudes (*15*). How will they change if car-clogged spaces give way to natural places where children can play wildly and others reflect quietly?

REFERENCES

1. American Psychological Association Task Force on Urban Psychology, *Toward an Urban Psychology: Research, Action, and Policy* (American Psychological Association, Washington, DC, 2005).
2. T. Hartig, R. Mitchell, S. de Vries, H. Frumkin, *Annu. Rev. Public Health* **35**, 207–228 (2014).
3. European Commission Directorate-General for Research and Innovation, *Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions and Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities'* (European Commission, Brussels, 2015).
4. S. Milgram, *Science* **167**, 1461–1468 (1970).
5. J. Peen, R. A. Schoevers, A. T. Beekman, J. Dekker, *Acta Psychiatr. Scand.* **121**, 84–93 (2010).
6. F. K. Judd *et al.*, *Aust. N.Z. J. Psychiatry* **36**, 104–113 (2002).
7. A. J. Ferrari *et al.*, *Psychol. Med.* **43**, 471–481 (2013).
8. T. Hartig *et al.*, in *Forests, Trees and Human Health*, K. Nilsson *et al.*, Eds. (Springer, Dordrecht, 2011), pp. 127–168.
9. S. M. E. van Dillen, S. de Vries, P. P. Groenewegen, P. Spreeuwenberg, *J. Epidemiol. Community Health* **66**, e8 (2012).
10. I. Alcock, M. P. White, B. W. Wheeler, L. E. Fleming, M. H. Depledge, *Environ. Sci. Technol.* **48**, 1247–1255 (2014).
11. T. S. Eisenman, *J. Plann. Hist.* **12**, 287–311 (2013).
12. D. C. Rouse, I. F. Bunster-Ossa, *Green Infrastructure: A Landscape Approach* (Planning Advisory Service Report 571, American Planning Association, Chicago, 2013).
13. P. H. Kahn Jr., *Technological Nature: Adaptation and the Future of Human Life* (MIT Press, Cambridge, MA, 2011).
14. P. H. Kahn Jr., P. H. Hasbach, Eds., *The Rediscovery of the Wild* (MIT Press, Cambridge, MA, 2013).
15. F. G. Kaiser, T. Hartig, A. Brugger, C. Duvier, *Environ. Behav.* **45**, 369–398 (2013).

10.1126/science.aaf3759

PERSPECTIVE

Meta-principles for developing smart, sustainable, and healthy cities

Anu Ramaswami,[1]* Armistead G. Russell,[2] Patricia J. Culligan,[3] Karnamadakala Rahul Sharma,[1] Emani Kumar[4]

Policy directives in several nations are focusing on the development of smart cities, linking innovations in the data sciences with the goal of advancing human well-being and sustainability on a highly urbanized planet. To achieve this goal, smart initiatives must move beyond city-level data to a higher-order understanding of cities as transboundary, multisectoral, multiscalar, social-ecological-infrastructural systems with diverse actors, priorities, and solutions. We identify five key dimensions of cities and present eight principles to focus attention on the systems-level decisions that society faces to transition toward a smart, sustainable, and healthy urban future.

By the year 2050, the number of people living in cities is expected to increase by about 2.5 billion (*1*). It is estimated that over 60% of the urban areas that will exist by 2050 have yet to be built, indicating that there will be massive new infrastructure requirements, particularly in Asia and Africa (*2*). Simultaneously, existing cities worldwide are aging and much in need of infrastructure replacement.

Infrastructures—defined broadly as the systems that provide water, energy, food, shelter, transportation and communication, waste management, and public spaces (*3*)—are essential to support human well-being and economic development. However, aggregated globally, these seven infrastructure sectors currently place a large burden on the environment and have a considerable impact on human health (Fig. 1). Urban demands dominate these effects; for example, ~70% of global greenhouse gas (GHG) emissions are attributable to cities (*1*). Because physical infrastructures have life spans of 30 to 50 years, the large imminent global requirement for new urban infrastructure presents a historic opportunity for change. The question is, how can urban infrastructure transformations in the 21st century advance the environmental sustainability and human well-being of our cities by taking advantage of the enormous potential offered by data science and technology?

Although information and communication technologies are important for developing smart, sustainable, healthy cities (*4*), we argue that a larger understanding of urban infrastructure systems is necessary to move from data to information to knowledge and, ultimately, to action for urban sustainability and human well-being.

[1]Hubert H. Humphrey School of Public Affairs, University of Minnesota, Minneapolis, MN 55455, USA. [2]School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355, USA. [3]Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, NY 10027, USA. [4]ICLEI–Local Governments for Sustainability, South Asia Secretariat, New Delhi 110020, India.
*Corresponding author. Email: anu@umn.edu

With infrastructure as the focus, we identify five key dimensions of cities and present eight principles to help guide urban transformations toward sustainability and health, drawing on examples from the United States, China, and India.

Key dimensions

Economic opportunity is a key driver for urbanization, and infrastructure is a prime enabler. Multi-city data sets are emerging that describe scaling relationships among urban population growth, gross domestic product (GDP), household incomes, and infrastructure-related parameters such as financial investments, energy and water use, and land and road expansions (*5*). Cities with different economic structures (e.g., highly industrial, highly commercial, or mixed economy) are known to exhibit different socio-spatial patterns of development (i.e., urban form) that affect infrastructure design. Yet basic city-level data on urban GDP, sectoral employment, and household incomes are sparse in many developing nations and in smaller cities and towns, where much urban growth is projected to occur.

Urban form or morphology describes the evolving interaction between physical space and human activity in cities. Numerous data sets, from census data to aerial and satellite photographs and remote sensing information, are being integrated to enable planners to characterize urban form. Urban complexity science is advancing new measures (*4*) that focus not only on population density, connectivity, proximity to jobs and services, and diversity and intensity of urban activities but also on understanding self-similarity across scales (from blocks to neighborhoods to cities) and patterns of social segregation (e.g., of migrant and informal populations in a city). Urban form represents the foundation upon which infrastructure develops, shaping energy and material use; access to and contiguity of water bodies, green space, and other critical ecosystems; and urban equity and well-being.

Infrastructure design and socio-spatial disparities within cities are emerging as critical determinants of human health and well-being.

Cities are grappling with multiple and multiscalar health risks pertaining to infrastructure, such as food and water insecurity in households, neighborhood designs that inhibit active living, regional air and water pollution, and extreme heat, cold, and flooding that may be exacerbated by climate change (*6*). Socioeconomic disparities often shape exposure to the various risk factors and mediate and modulate the health outcomes. Addressing these diverse social, environmental, and infrastructural risk factors represents a new paradigm for urban public health. The World Health Organization (*7*) and the Centers for Disease Control and Prevention in the United States (*8*) recommend community-based participatory health planning that connects local capacities with infrastructure, using advanced information processing systems and ambient sensing. Making these connections is challenging, requiring overarching frameworks that connect diverse data and processes across scales to support action (*9*).

The environmental impacts of cities are numerous and multiscalar, driven by the transboundary nature of their infrastructure. Cities produce less than 10% of their food and rely on water, energy, fuel, and construction materials from external sources. Sustainable urban system studies are advancing urban supply-chain footprinting techniques that capture infrastructure use within the city (shaped by economic activity and urban form) in combination with transboundary infrastructure supply chains and trade networks. Such transboundary footprints (*10*) characterize the broader environmental impact of all seven urban infrastructure sectors on various resources (e.g., energy, water, and nutrients) and on pollution. Transboundary analysis considers how cities can reduce environmental impacts within their boundaries and across their supply chains and what the risks are to cities from supply disruptions. Cities are beginning to track their transboundary greenhouse gas footprints (*11*) while incorporating supply disruptions (e.g., power cuts, water scarcity, and food and fuel disruptions) into urban quality-of-life metrics (*12*).

The intertwined outcomes of environmental sustainability and human well-being require understanding interactions among all seven sectors within a city in terms of local-scale quality-of-life impacts; at the same time, it is also necessary to connect the transboundary infrastructures with regional and global environmental and health impacts, engaging multiple actors and institutions across scales (Fig. 2). Understanding and enhancing the capacity of social, policy, and governance networks therefore holds the key to change. Analyses of social norming and social networks are yielding insights about peer learning with respect to environment and health in cities; mapping of policy actors reveals how information is shared across sectors and scales (*13*). The five key dimensions outlined here—economic opportunity, urban form, social-infrastructural disparities and human well-being, transboundary infrastructure-environment dynamics, and cross-scale multisector governance—serve as the framework (Fig. 2) from which we draw principles for action.

"...a larger understanding of urban infrastructure systems is necessary to move from data to information to knowledge and, ultimately, to action for urban sustainability and human well-being."

Basic principles for transforming cities

1) Focus on providing and innovating basic infrastructure for all. Basic and affordable water, energy, sanitation, and transportation have long been recognized as important for all cities but have been difficult to attain in some cases, often because of rapid in-migration, unplanned urban expansions, and challenges in infrastructure financing. With 30 to 40% of the population in several cities in Asia and Africa living in slums (*2*), a healthy city must prioritize basic infrastructure for all. Many smart-city discussions focus on high technology, overlooking more basic, yet innovative, equitable solutions that are emerging, such as fit-for-purpose point-of-use household water treatment in Chinese cities (*14*), water "ATMs" in Indian cities, and prioritization to support nonmotorized transportation in compact mixed-use urban neighborhoods.

2) Pursue dynamic multisector and multiscalar urban health improvements, with attention to inequities. Cities must strive to address health priorities, which vary widely across cities, within cities, and over time, by considering infrastructural, environmental, and sociocultural determinants at different scales (*9*). Such an approach could yield, for example, regional weather and air pollution forecasts that provide customized messaging to vulnerable populations, neighborhood-level health interventions, more equitable access to nutritious food and green spaces, and greater attention to sociocultural

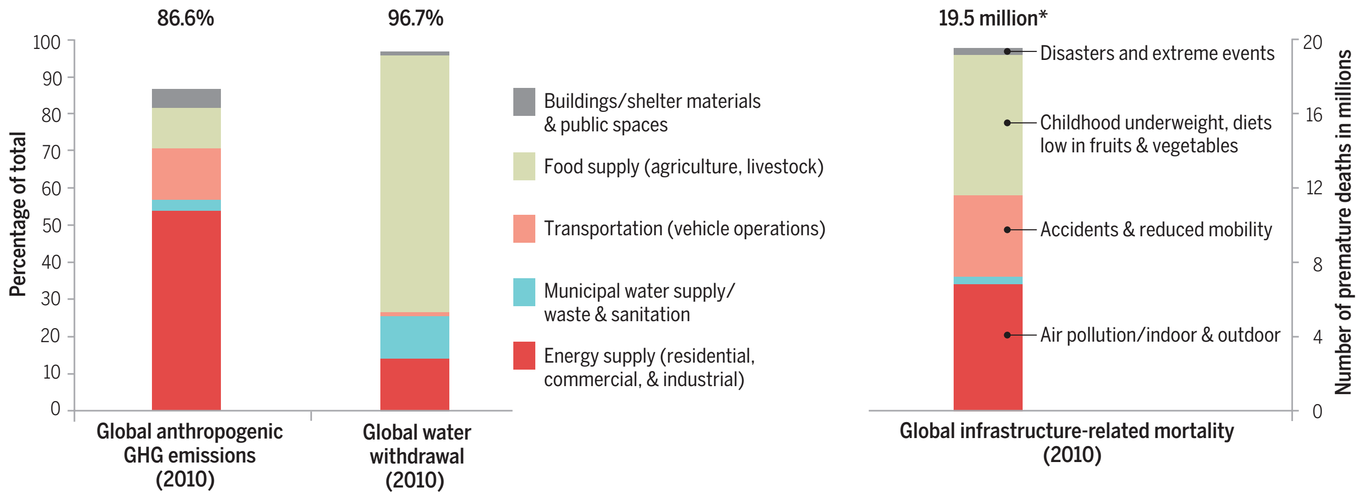

Fig. 1. Impacts of key infrastructure sectors. Shown are the impacts of urban infrastructure sectors on global anthropogenic GHG emissions (*20*), global water withdrawals (*21*, *22*), and global disease burden (*6*). GHG and water impacts associated with buildings and shelter materials include those of producing cement and steel, disaggregated by the authors based on various literature sources. Non-energy GHG emissions are shown for waste and sanitation. Transportation-related premature mortality is from accidents (*23*) and reduced mobility (*6*). The asterisk indicates that total deaths in the right column are non-additive because of overlap.

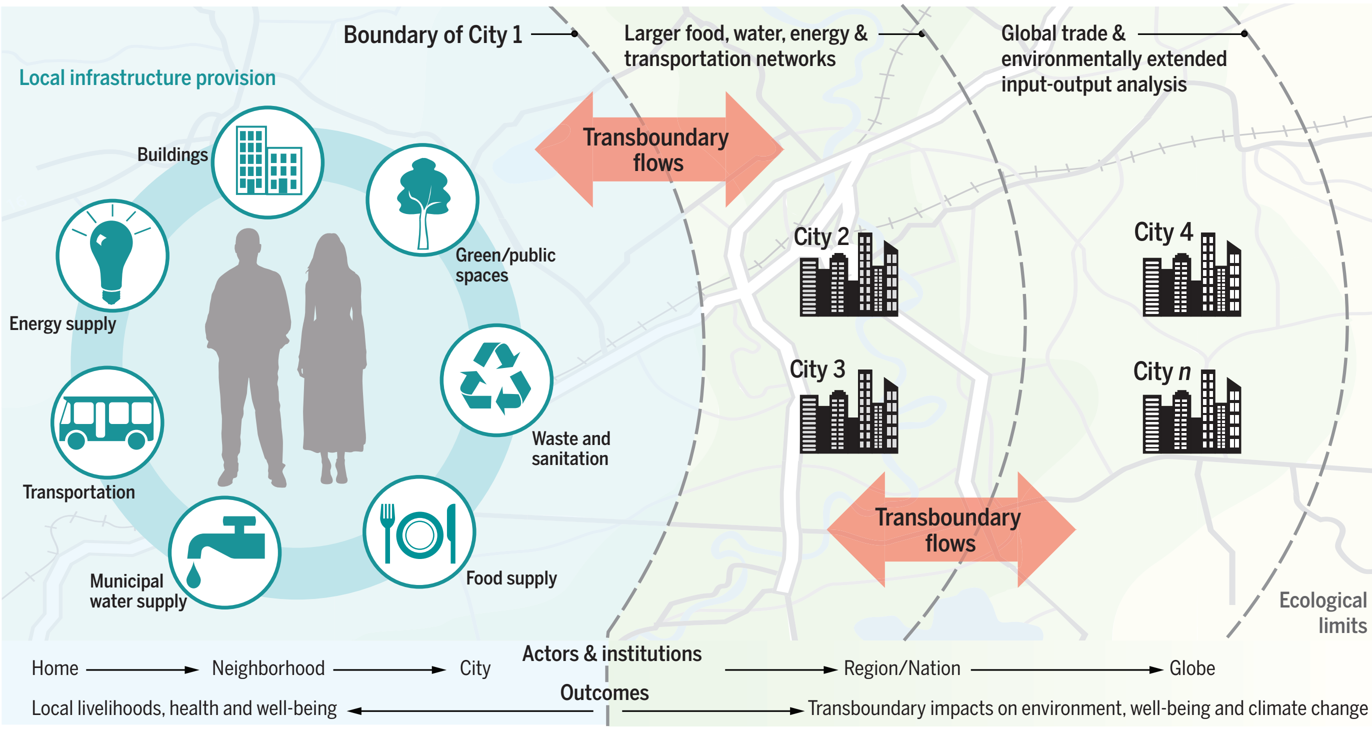

Fig. 2. Intersection of human activities and seven infrastructure sectors within a city, linked to natural ecosystems through transboundary infrastructures across scales. Actors and outcomes (health and sustainability) are also intertwined across scales.

assets that enhance quality of life and human well-being.

3) Focus on urban form and multisector synergies for resource efficiency. As populations urbanize, they become wealthier, increasing material consumption and environmental impact. To counter these effects, urban areas must increase resource efficiency, not by a few percentage points but by factors of 4 to 10. Such efficiency gains cannot come from single-sector interventions in a diffuse urban morphology. Research suggests that an optimally dense urban form, with a high intensity of diverse co-located activities, creates opportunities for systemic multisector infrastructure interventions, yielding the highest-efficiency gains. Advanced district energy systems that use energy cascading, exchange, and storage across industries, power plants, buildings, transportation, water, solid waste management, and renewable energy production offer tremendous potential (*15*). Knowledge of urban morphology, combined with temporal and spatial cross-sectoral infrastructure data, is essential.

4) Recognize diverse strategies for resource efficiency in different city types. A technology-oriented view of smart cities can result in translating high-efficiency solutions from one country or culture to another, where they may not work as well. For example, although tightly insulated, highly instrumented, all-day centrally cooled and heated buildings may be energy-efficient for the United States and the European Union, the same approach may not translate to the more vernacular architecture and informal user practices of Chinese apartments, which tend to be spot-cooled over short periods of time, greatly reducing resource intensity (*16*).

5) Integrate high- and vernacular technologies. Cities should seek local knowledge and systems-level understanding of different solution configurations. For example, municipal plants that convert solid waste to energy are not as effective in developing world cities. The waste streams have lower calorific value, having been sifted through by the informal sector of waste pickers who recycle more than 200 types of waste paper and plastics, which creates greater systems efficiency in terms of material cycling while also promoting local livelihoods. Formalizing and integrating the expertise of waste pickers with state-of-the-art information and waste-to-energy technologies can create hybrid solutions, illustrated, for example, by India's recently revised solid waste management regulations (*17*).

6) Apply transboundary systems analysis to inform decisions about localized versus larger-scale infrastructure. Driven by goals of local self-reliance, efficacy, and anticipated health and well-being benefits, cities are increasingly focusing on more localized infrastructures, such as rooftop and community solar installations, community-supported urban farms, and apartment-scaled wastewater treatment plants. Improved information about transboundary environmental footprints and local well-being impacts are critical to clarify synergies and trade-offs between local versus larger-scale infrastructure networks.

7) Recognize coevolution of infrastructures and institutions (*15*). Matching the scale of engineered infrastructures with that of the institutions with which they must operate is key. For example, neighborhood-scale urban farms, solar gardens, and waste management systems will require new levels of coordination among homes, neighborhood associations, businesses, and city- and state-level governments. At the same time, technology can change institutions; for example, widespread deployment of sensors is enabling remote surveillance of distributed water and wastewater systems. Awareness of the need for new and evolving institutions to manage emerging smart infrastructure can help ease these transitions.

8) Create capacity and transparent infrastructure governance across sectors and scales. Cities need capacity—analytic, administrative, and political—to implement high-impact, cross-sector, cross-scale solutions. Some cities have created sustainability offices that are empowered to convene multiple city departments, and many are leveraging multilevel and cross-national policy-exchange networks (*18*). With the smart-city agenda requiring high-technology expertise, greater involvement of the private sector in infrastructure delivery is inevitable. Many cities are initiating public-private partnerships and/or special financing for smart-city development. These arrangements raise questions about ownership, equity, and governance (*19*). It is equally important to ask where all the information that enables a smart, sustainable, and healthy city will reside. Transparent and adaptive governance arrangements that are open to public input and scientific study will empower cities, and the world, to learn by doing.

These eight principles focus attention on higher-order, systems-level decisions that society must make to transition toward a smart, sustainable, and healthy urban future. To achieve the full potential of smart cities, discussions must move beyond data to envision cities as multisectoral, multiscalar, social-ecological-infrastructural systems with diverse actors, priorities, and solutions.

REFERENCES AND NOTES

1. K. C. Seto *et al.*, in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer *et al.*, Eds. (Cambridge Univ. Press, 2014), pp. 923–1000.
2. M. Swilling, B. Robinson, S. Marvin, M. Hodson, *City-Level Decoupling: Urban Resource Flows and the Governance of Infrastructure Transitions* (United Nations Environmental Program, 2013).
3. A. Ramaswami *et al.*, *J. Ind. Ecol.* **16**, 801–813 (2012).
4. L. Bourdic, S. Salat, C. Nowacki, *Build. Res. Inform.* **40**, 592–605 (2012).
5. L. M. A. Bettencourt, *Science* **340**, 1438–1441 (2013).
6. S. S. Lim *et al.*, *Lancet* **380**, 2224–2260 (2012).
7. World Health Organization (WHO), "Healthy cities," 2016; www.euro.who.int/en/health-topics/environment-and-health/urban-health/activities/healthy-cities.
8. Centers for Disease Control and Prevention, "Healthy Communities Program (2008–2012)," 2016; www.cdc.gov/nccdphp/dch/programs/healthycommunitiesprogram/.
9. Y. Rydin *et al.*, *Lancet* **379**, 2079–2108 (2012).
10. T. Hillman, A. Ramaswami, *Environ. Sci. Technol.* **44**, 1902–1910 (2010).
11. ICLEI-USA, *U.S. Community Protocol for Accounting and Reporting of Greenhouse Gas Emissions* (ICLEI-USA, 2016); http://icleiusa.org/publications/us-community-protocol/.
12. International Standards Organization, "Sustainable development of communities—Indicators for city services and quality of life," 15 May 2014; www.iso.org/iso/catalogue_detail?csnumber=62436.
13. T. Lee, S. van de Meene, *Policy Sci.* **45**, 199–220 (2012).
14. T. Tao, K. Xin, *Nature* **511**, 527–528 (2014).
15. H. Lund *et al.*, *Energy* **68**, 1–11 (2014).
16. International Energy Agency and Tsinghua University, *Building Energy Use in China: Transforming Construction and Influencing Consumption to 2050* (International Energy Agency, 2015).
17. Government of India, Ministry of Environment and Forests, press release (5 April 2016); http://pib.nic.in/newsite/PrintRelease.aspx?relid=138591.
18. H. Bulkeley, M. Betsill, *Env. Polit.* **14**, 42–63 (2005).
19. R. G. Hollands, *City* **12**, 303–320 (2008).
20. Intergovernmental Panel on Climate Change, *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer *et al.*, Eds. (Cambridge Univ. Press, 2014).
21. AQUASTAT, Food and Agriculture Organization, "Water uses," 2016; www.fao.org/nr/water/aquastat/water_use/index.stm).
22. International Energy Agency, "Water for energy," 2016; www.worldenergyoutlook.org/resources/water-energynexus/.
23. WHO, *Global Status Report on Road Safety 2013: Supporting a Decade of Action* (WHO, 2013); www.who.int/violence_injury_prevention/road_safety_status/2013/en/.

ACKNOWLEDGMENTS

The authors are grateful for support from NSF (Partnership for International Research and Education award 1243535 and Sustainability Research Networks award 1444745) and from the U.S. Agency for International Development and the National Academy of Sciences (Partnership for Enhanced Engagement in Research subgrant 2000002841). The principles outlined here were discussed at a workshop convened by ICLEI–South Asia and the University of Minnesota in January 2016, which was attended by more than 40 city officials and policy-makers from the United States, China, and India.

10.1126/science.aaf7160

PERSPECTIVE

Hidden linkages between urbanization and food systems

Karen C. Seto[1]* and Navin Ramankutty[2]*

Global societies are becoming increasingly urban. This shift toward urban living is changing our relationship with food, including how we shop and what we buy, as well as ideas about sanitation and freshness. Achieving food security in an era of rapid urbanization will require considerably more understanding about how urban and food systems are intertwined. Here we discuss some potential understudied linkages that are ripe for further examination.

The rise of urbanization is transforming food systems in many areas, including production on the farm, processing and packaging, distribution and retail, and consumption at the table. Cities concentrate people who live and work in close proximity and facilitate social interaction, which results in a greater variety of available food choices and creates new habits and tastes. Though a few links between urbanization and food systems are attracting increased attention from researchers, we discuss many poorly understood linkages that require further study if we are to achieve food security in an urban era.

Urbanization is a complex phenomenon that involves change in multiple dimensions, including a growing percentage of people who live in urban areas; the expansion of built environments; and changing norms, cultures, and ways of living. Most of what we know about how urbanization affects food systems is focused on two issues: the physical expansion of urban areas (food supply side) and changes in diet (food demand side). A widely expressed concern about urbanization is that expanding cities will result in widespread loss of croplands. Between 1970 and 2000, our global urban footprint expanded by 58,000 km^2 (*1*). By 2030, built-up areas are forecasted to nearly triple in size over the 2000 area, an increase of 1.2 million km^2 (*2*). However, croplands, which account for 12% of the world's ice-free land cover, exceed urban areas, which take up less than 3% (*3*). Though this difference in total area suggests that expansion of urban areas will have a minimal effect on Earth's total cropland, two qualifications are important.

First, because built-up areas are growing faster than urban populations in most parts of the world (*1*, *4*), cropland loss is likely to be acute in countries where urban population growth rates are high and the economy is largely agrarian. Thus, the loss of cropland due to urban expansion is likely to be more of a regional problem than global one. For the affected regions in particular, strategies are needed to manage urban expansion in ways that reduce pressure on farmland, inefficient land-use patterns, and leapfrog development. Toward these goals, the United Nations Human Settlements Programme (UN-Habitat) is supporting efforts to minimize urban sprawl by encouraging densification and more compact cities in countries such as Brazil, Ecuador, and Egypt. An alternate strategy is to safeguard agricultural land from development. The Canadian province of British Columbia established the Agricultural Land Reserve, a land-use zone intended to protect fertile agricultural land from development.

Second, given that cities historically developed in fertile agricultural areas, future expansion of built-up areas will probably encroach on productive agricultural land. This has already occurred in India, Vietnam, China, Turkey, and the United States, where urban expansion has resulted in the loss of prime agricultural land. Loss of the most productive agricultural land leads to decreased average cropland productivity (*5*), which is not a promising trend at a time when closing yield gaps is considered important (*6*, *7*). Furthermore, the loss of agricultural land may result in the need to expand crop production into marginal and fragile lands, as well as other ecosystems. In the tropics, deforestation due to agricultural land expansion is estimated at 12 million ha per year (*8*). Notwithstanding these qualifications, the effect of urban expansion on farmland loss is unlikely to be the most important influence of urbanization on food systems.

On the demand side, it is well documented that the diets of urban and higher-income societies require costly expenditures of land, water, and energy (*9*, *10*). With few exceptions, highly urbanized countries consume more animal protein—in the form of pork, poultry, beef, and dairy products—than the world average. Globally, the average meat consumption per capita is 36.9 kg per year, but there is huge variation between countries, with higher-income countries consuming 81.8 kg per year per capita compared with 17.2 kg per year in lower-income countries (*9*). In the United States, where 81% of the population lives in urban areas, per-capita meat consumption is 89.7 kg per year. In China, per-capita

[1]Yale School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA. [2]Liu Institute for Global Issues and Institute for Resources, Environment and Sustainability, The University of British Columbia, Vancouver, British Columbia V6T 1Z2, Canada.
***Corresponding author. Email: karen.seto@yale.edu (K.C.S.); navin.ramankutty@ubc.ca (N.R.)**

Meta-principles for developing smart, sustainable, and healthy cities
Anu Ramaswami, Armistead G. Russell, Patricia J. Culligan, Karnamadakala Rahul Sharma and Emani Kumar (May 19, 2016)
Science **352** (6288), 940-943. [doi: 10.1126/science.aaf7160]

Editor's Summary