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Linking Urbanization and the Environment: Conceptual and Empirical Advances

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Abstract

Urbanization is one of the biggest social transformations of modern time, driving and driven by multiple social, economic, and environmental processes. The impacts of urbanization on the environment are profound, multifaceted and are manifested at the local, regional, and global scale. This article reviews recent advances in conceptual and empirical knowledge linking urbanization and the environment, focusing on six core aspects: air pollution, ecosystems, land use, biogeochemical cycles and water pollution, solid waste management, and the climate. We identify several emerging trends and remaining questions in urban environmental research, including (*a*) increasing evidence on the amplified or accelerated environmental impacts of urbanization; (*b*) varying distribution patterns of impacts along geographical and other socio-economic gradients;

(*c*) shifting focus from understanding and quantifying the impacts of urbanization toward understanding the processes and underlying mechanisms; (*d*) increasing focus on understanding complex interactions and interlinkages among different environmental, social, economic, and cultural processes; and (*e*) conceptual advances that call for articulating and using a systems approach in cities. In terms of governing the urban environment, there is an increasing focus on public participation and coproduction of knowledge with stakeholders. Cities are actively experimenting toward sustainability under a plethora of guiding concepts that manifests their aspirational goals, with varying levels of implementation and effectiveness.

Contents

1. INTRODUCTION

Driven by migration as well as indigenous growth within cities, by 2050, a 2.5 billion increase in urban population is expected, with 90% of the increase concentrated in Asia and Africa (1). Urbanization, driving and driven by multiple social, economic, and environmental processes, is one of the biggest social transformations of modern time (2). The environmental implications of rapid urbanization are profound and far reaching, with the impacts often outpacing the population growth. In China, urban built-up land grew much faster than urban population, driven by a positive causal feedback between urbanization and economic growth (3). Carbon emissions from urban areas increased even faster than urban land expansion, resulting in a significant increase in the carbon intensity of built-up areas in China (4). Positive causal relationships were also found between urbanization, energy consumption and carbon emission in China (5) and Southeast Asia (6).

The conceptual framework of cities as the driver and main bearer of environmental changes across local, regional, and global scape, as illustrated in Grimm et al. (7), has been pivotal in shaping the discourse on urbanization and environmental change. Increasing evidence suggests that the pattern and magnitude of the linkage between urbanization and environmental impact may vary and change over time, depending on the physical, social, and economic contexts as well as the development trajectories. The physical, environmental, social, and economic processes are often interlinked, with complex trade-offs and synergies (8). A systems approach that integrates multiple disciplinary approaches in natural science, engineering, and humanities, bringing together researchers and practitioners, is called for (8).

Increasingly, the perception and discourse toward urbanization and environment is shifting from challenges and problems toward opportunities and solutions. Many cities must confront expanding challenges from population growth that outpaces infrastructure development, growing slums and informal settlements, changing demographic characteristics, social inequality, economic fluctuations, pollution, local changes in climate and water systems, and many other stressors (9). At the same time, the highest potential to provide solutions to local as well as global environmental challenges also lies within cities, given the concentration of financial, knowledge, and innovation (both technological and cultural) capacities. Such a shift is beyond rhetoric; although urban rivers are often found to be hot spots of nitrogen concentration (10), studies have also found that urbanization in some highly developed watersheds can bring about improvement in water quality, given increasing wastewater management infrastructure (11). There has been a significant increase in literature focusing on urban experiments and urban sustainability transition since 2010, with increasing evidence from the developing world (12, 13). Examining the role of local experiments and innovative practices in sustainability transitions reveals potential, albeit with varying degrees of significance (13–15). The abundance of concepts and phrases used in policy and practice—e.g., *sustainable*, *smart*, *eco-*, *resilient*, *knowledge*, *information*, *low-carbon* cities (16)—reflects the abundance of initiatives of cities and their linked but differing aspirations.

From the policy perspective, cities and urban issues are receiving increasing attention in international policy processes. The UN Sustainable Development Goals includes an urban goal as one of the 17 final goals. Because of their vital role in climate mitigation and adaptation, cities have become front-stage actors since the Intergovernmental Panel on Climate Change (IPCC) Paris Climate Agreement in 2015. The New Urban Agenda adopted at the UN Habitat III Conference aims to guide urban development in the next two decades toward sustainable, livable, and resilient futures (17). An increased involvement of science in these international urban policy processes and practice is called for (8, 18).

This article reviews recent advances in knowledge on urbanization and environmental linkages, most from papers published after 2010. Section 2 presents a brief review of conceptual advances, followed by Section 3, which is an examination of the advances in six core aspects of urbanization and environment—namely air pollution, ecosystems, land use, biogeochemical cycles and water pollution, solid waste management, and the climate. Emerging research trends and remaining questions are discussed in Section 4. Section 5 discusses the governance of urban-environmental linkages. Section 6 presents conclusions.

2. CONCEPTUAL ADVANCES IN UNDERSTANDING URBAN SYSTEMS

There has been a surge of recent literature exploring the complexity of urban systems and calling for an integrated systems approach in urban research and practice. The study of urban ecology has shifted from ecology in and of cities to embracing an ecology for cities (19). Ecology in cities research has shown that cities and urbanization processes modify environments often, causing impaired ecology of cities. Ecology of cities is fundamentally a systems science, and it integrates multiple disciplinary approaches such as ecology and sociology, along with transdisciplinary perspectives such as complexity, systems thinking, and sustainability, to study the city as a complex, highly interactive system (20). Ecology for cities seeks to deliver applied knowledge to advance urban sustainability decision making and practice (21). The emerging social-ecological-technical systems (SETs) perspective (9, 22, 23) aims to advance beyond the limitations of more traditional urban studies using a purely socio-technological approach that tends to exclude ecological functions, or a social-ecological approaches that may overlook critical roles of technology and infrastructure in the structure and functioning of urban systems. In this way the SETs approach builds on the theoretical foundation in urban ecology that views cities as ecosystems but explicitly recognizes the fundamental interacting urban systems domains that must be examined together to further advance the field. Another attempt toward a more integrative approach among different disciplines is via a conceptual bridge between urban ecosystem studies and the urban energy and material flow studies, identifying eight ecosystem characteristics that can be revealed from the empirical work of the latter (24). Telecoupling is another recent conceptual advance that seeks to understand unintended consequences beyond the intended system boundaries (25). Research exploring intersects of multiple processes in urban space is emerging, e.g., the food-water-energy nexus in urban space (26, 27). One common aspect of these recent studies is that they are all pointing to the importance of the integrated systems approach, but it is not always explicit what that actually means.

In an attempt to define and advance the systems approach for sustainable cities, Bai et al. (8) consider urban systems as including the following five characteristics: (*a*) Cities are open systems with a constant exchange of resources, products, services, waste, people, ideas, and finance with the external world; (*b*) cities are complex, self-organizing, adaptive, and constantly evolving; (*c*) cities encompass multiple actors with varying responsibilities and priorities, and involving processes that transcend institutional boundaries; (*d*) cities are embedded in the broader ecological, economic, technical, institutional, legal, and governance structures that often constrain their systemic function; and (*e*) urban processes are causally interlinked, within interactions and feedbacks that result in intended and unintended consequences. **Figure 1** shows the conceptualization of the urban system structure and interlinkages within and beyond the city. Emphasizing context, vision, goals, actors, diversity/interdependencies, and flexibility/adaptability are identified as important

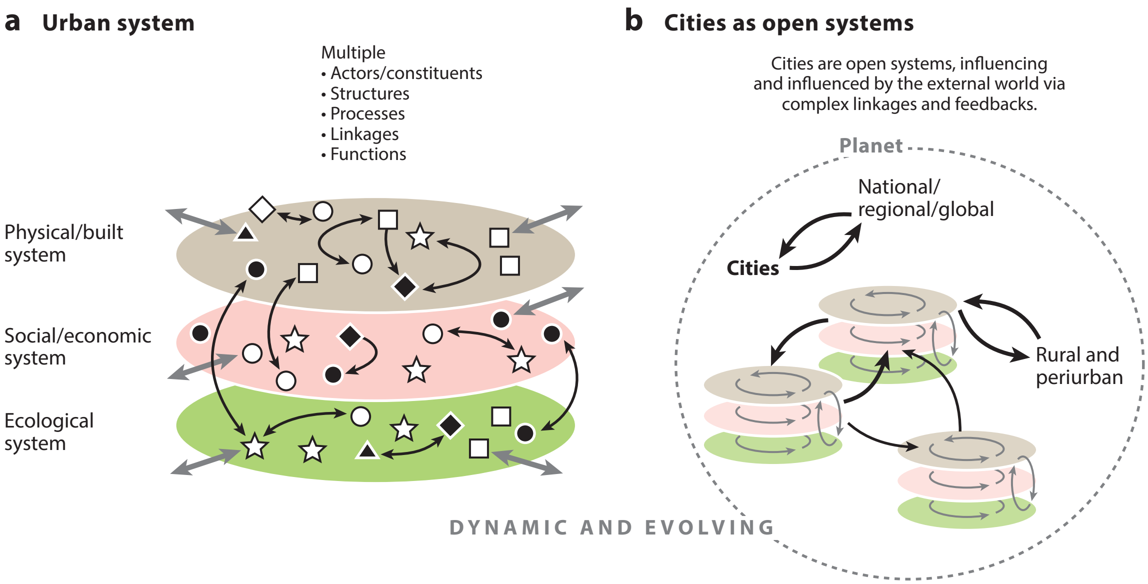

Figure 1

Urban system structure and interlinkages, focusing more on (*a*) the internal structure and highlighting (*b*) external linkages and interactions of cities. The symbols represent various actors/constituents, structure, and processes across physical/built, social/economic, and ecological subsystems. The arrows represent complex processes and linkages within and between cities, and between cities and their hinterlands. The actors and constituents are typically self-organizing, and the structure, processes, and linkages and functions are dynamic and evolving, with nonlinear pathways. Figure reprinted from Reference 8.

principles in a systems approach. To promote a systems approach, it is essential to radically redesign the urban-related institutional setup; promote regenerative culture, behavior, and design in cities; explore ways to finance a systems approach, and promote a new and enhanced role for science.

Although not yet a mainstream practice, the systems approach is starting to be adopted in urban practice. In Bangalore, for example, integrated systems thinking is applied for lake restoration, bringing in a landscape perspective and also integrating biophysical and ecological solutions with inclusive social approaches, and linking communities with states' governance processes to think more systemically (28). Another example is the rapid proliferation of "Sponge City" in China, where increasing severe flood in cities is to be abated by combining nature based solutions with other innovative technologies to convert impervious urban surfaces into pervious ones and reduce direct runoff of storm water (29). This is a fundamental shift from engineering-based, control-oriented thinking toward a systems approach seeking solutions from multiple sectors, which is proven to be much more effective with significantly lower cost.

3. SIX MAJOR URBAN ENVIRONMENTAL CHALLENGES

3.1. Air Pollution

Air pollution has been the major environmental concern in cities around the world (30). Air pollution in cities mainly comes from the emissions from intensive human activities. However, cities at different stages of development may have very different emission sources of air pollutants (31). The dominant source of pollution among European and American megacities is transport emissions (32), whereas in the rest of world, cities have very diversified emissions sources, including industry, power generation, transport, construction, and household emissions (33). In wintertime in Beijing, household use of solid fuel for heating and cooking contributed 22% of $PM_{2.5}$ [particulate matter with aerodynamic diameter equal or smaller than 2.5 μm concentrations (34)].

High-population-density air pollution—especially the severe air pollution many developing cities experience—is posing serious health risks to the urban residents. The highest premature mortality rates are found in the Southeast Asian and Western Pacific regions, where more than a dozen of the most highly polluted megacities are located (35). A recent study in China shows that 83% of the population lived in areas where $PM_{2.5}$ concentrations exceeded the Chinese Ambient Air Quality Standard of 35 $\mu g\ m^{-3}$, whereas high-population-density areas, such as megacities Shanghai, Beijing, and Tianjin, exhibited the highest mortality rates per square kilometer attributed to air pollution (36).

Decades of efforts have led to significant improvements in the air quality in developed countries (37). Large cities in North America, Europe, and Latin America have better air quality than those in other continents, whereas those in China and India have the worst air quality (38). The severe haze pollution events experienced by many cities in China were driven to a large extent by secondary aerosol formation (39), and the particle compositions in Beijing exhibit a similarity to those commonly measured in many global areas, which is consistent with the chemical constituents dominated by secondary aerosol formation (40). The heterogeneous chemical processes potentially played important roles in the formation of an air pollution complex and gray haze; e.g., the coexistence of high concentrations of primary and secondary gaseous and particulate pollutants provides a large amount of reactants for heterogeneous reactions on the surface of fine particles, thereby accelerating formation of the air pollution complex and gray haze (41). In a recent model study, Cheng et al. (42) suggested that the aerosol water serves as a reactor, where the alkaline aerosol components trap sulfur dioxide (SO_2), which is oxidized by nitrogen dioxide (NO_2) to form sulfate, whereby high reaction rates are sustained by the high neutralizing capacity of the atmosphere in northern China. These studies suggest that key to reducing the urban particulate matter level in China would be the regulatory controls of gaseous emissions for volatile organic compounds and nitrogen oxides ($NOx = NO_2 + NO$) from local transportation, as well as SO_2 from regional industrial sources (40).

In addition to the complex chemical reaction that leads to the formation of severe air pollution in urban areas, changing meteorological fields resulting from urbanization can also play a major role. A study in Beijing, Tianjin, Hebei, and the Yangtze River Delta areas on meteorology and ozone concentrations show that urbanization causes an increase in temperature, planetary boundary layer height, and daytime ozone concentrations and a decrease in wind speed, the combined effects of which can be equivalent to a 20% increase in emissions (43).

Is the level of the air pollution in cities correlated with the size of the city or the population density? Parrish & Zhu (37) hypothesized that the concentrations of primary air pollutants, such as NO_2, grow as a power-law function of population, N^β, where N is the population size and the exponent β is between 0 and 1. As each person is exposed to the pollutant concentration, the population exposure increases roughly as $N^{1+\beta}$, and air pollution thus becomes a rapidly increasing health problem as cities grow (37). This hypothesis raised an important question: How big should a city be, from the perspective of air pollution and its health risks?

To further examine this hypothesis, Lamsal et al. (44) derived a global distribution of ground-level NO_2 concentrations from tropospheric NO_2 columns retrieved from the Ozone Monitoring Instrument. They found that urban NO_2 pollution, as with other urban properties, is a power-law scaling function of the population size. The value of the exponent varies by region from 0.36 for India to 0.66 for China, reflecting regional differences in industrial development and per capita emissions. Important differences between changes in urban characteristics and pollutant levels, especially NO_2, on the basis of city size were also observed (45). However, when it comes to $PM_{2.5}$, which is from both primary emission (directly from emission sources) and secondary production (the pollutants produced through the chemical reaction in the atmosphere, of the primary emission), the power law is very different. The relationships between urban population size and $PM_{2.5}$ concentrations in large cities in North America, Europe, and Latin America showed little fluctuation or a small increasing trend, but those in Africa and India represent a U-shaped relationship and in China represent an inverse-U-shaped relationship (38). Another study by Sarzynski (46) confirms that urban pollution, represented by four air pollutants—NO_X, non-methane volatile organic compounds (VOCs), carbon monoxide (CO), and SO_2—is associated primarily, but not exclusively, with demographics, i.e., pollution likely to increase with population growth. These findings suggest that urban design and land-use policies can have substantial impacts on local air pollution levels (45).

Air pollution and its health risks are closely linked with the scale of urbanization across the world. It is one of the most important and complicated challenges human society is facing today. Scientific research and controlling policies implemented so far all suggest that an integrated and comprehensive solution is required, which integrates urban planning, clean energy, energy efficiency, and innovation in transportation (31). At the moment, efforts to achieve cobenefits of improving air quality and reducing climate change should have a high priority (30, 32, 37).

3.2. Biogeochemical Cycles and Water Pollution

Urbanization has profound impacts on biogeochemical cycles. First of all, urban ecosystems have elevated fluxes (and thus emission) of nutrients and chemical contaminants per unit of land. For example, in China, urban built-up areas, which make up less than 1% of the country's total land area, harbor more than 50% of its population (47). This means a much higher concentration of nutrient fluxes in urban areas than elsewhere. In addition, both biogeochemical cycles in urban areas are highly engineered and directed through various infrastructures and changed hydrological cycles such as increased impervious surfaces and the associated increase of stormwater. The impacts on the environment of such engineered and directed cycles depend, to a large extent, on the level and effectiveness of the infrastructure. In developing countries, due to the lack of sufficient investment in infrastructure compared to the rapid rate of urbanization, the environmental quality is being rapidly degraded. Furthermore, the ecosystem structure in urban areas is altered, often leading to a reduced capacity of ecosystem services such as water purification and pollution attenuation, which further exacerbates the problems associated with insufficient infrastructure.

Intensive discharge of nutrients and contaminants from urban areas, combined with the increase in impervious surfaces following urban expansion, can lead to a consistent decline in the health of urban aquatic ecosystems, a condition usually referred to as the urban stream syndrome (48). For example, by using six-year monitoring data in Hangzhou, China, Zhang et al. (10) demonstrated that ammonium concentrations in urban rivers were three to five times higher than in nonurban rivers in the region. Increased urban stormwater runoff associated with increasing impervious surfaces contributes significantly to the urban stream syndrome. With the use of stable isotopes of nitrogen, oxygen, and hydrogen, it was shown that there could be dynamic changes in nitrogen sources (air deposition versus chemical fertilizers) during a stormwater event (49). However, the impacts of urbanization on water quality are not universal, and they depend very much on how well the urban environment and infrastructure are managed. For example, stream and river restoration to increase hydrologic connectivity and in-line stormwater ponds can significantly improve water quality (50). Improvements in urban planning and water treatment standards will also alleviate the negative impacts of urbanization on environmental quality (11).

Different metal pollutants show different levels of concentration in aquatic systems along the urban-rural gradient. For example, Zhao et al. (51) demonstrated that along the urban-rural gradient in the Beijing metropolitan area, concentrations of metals in road-deposited sediments from central urban and suburban areas were much higher than those from rural areas, and thus potentially contribute to the metal pollution of urban aquatic systems through surface runoff. Yu and colleagues (52–54) explored changes in aquatic environmental quality along the south section of the Grand Canal in the Yangtze River Delta, China, an area with varying levels of urbanization—with towns, two small cities, three mid-sized cities, and one large city. The results show varying patterns. In urban and suburban waterscape parks in Shanghai, urban enrichment of sedimentary anthropogenic metals (Cd, Cu, Pb, Zn) was found, with the levels in urban parks doubled or tripled compared to suburban ones (55, 56). However, the multiple urban gradients along the Grand Canal showed varying pattern. While the concentration of agriculture-sourced Cd showed consistent decrease from towns to large cities, Pb from atmospheric deposition showed no difference, and urban-sourced Cu and Zn increased from towns to small cities and then gradually decreased in mid-sized and large cities. The inverse-U pattern of urban-sourced Cu and Zn seems to follow the typical environmental Kuznets curve; i.e., pollution increases initially with increased urbanization and then reduces as the cities become larger and richer and equipped with better infrastructure.

Micropollutants are ubiquitous in urban aquatic environments, and include a variety of organic contaminants, such as pharmaceuticals and personal care products (PPCPs), as well as industrial chemicals. Micropollutants usually exist in low concentrations in the environment ranging from pg L^{-1} to ng L^{-1} or in some cases up to μg L^{-1}. Although in low concentrations, micropollutants may pose detrimental risks to the ecosystem and humans. Micropollutants are commonly detected in influents and effluents of wastewater treatment plants, and removal efficiency varies greatly between compounds (57). In Lake Geneva, a study showed a significant plume of wastewater-derived micropollutants, resulting in up to 70-fold elevation of pharmaceutical concentrations compared to the background value, and some of these chemicals were found to pose an ecotoxicological risk (58).

In addition to chemicals, pollution by fecal and pathogenic bacteria and antibiotic resistance genes is also widespread in urban environments, particularly urban aquatic environments. Pollution of fecal and pathogenic bacteria mainly results from poor waste treatment facilities and overflows under flooded conditions in urban systems. Researchers suggest that fecal indicator bacteria are the top cause of river and stream impairments in the United States (59, 60). A high abundance of antibiotic resistance genes is often detected in sewage sludge (61).

Pollutants from aquatic systems can be transported to soils through irrigation with reclaimed water and urban-impacted river/stream water, with potential health impacts. Ferro et al. (62) reported that irrigation with treated wastewater can lead to the accumulation of carbamazepine and thiabendazole in soil and in lettuce grown in it. In a large-scale survey of wastewater-irrigated soils in northern China, Khan et al. (63) demonstrated that there was substantial build-up of heavy metals in wastewater-irrigated soils in the Beijing-Tianjin periurban area, and vegetables grown in these soils may pose health risks given accumulation of heavy metals. In a similar survey in this region, Wang et al. (64) found that both air deposition and uptake from soil contributed to the accumulation of polycyclic aromatic compounds (PAHs) in vegetables, and air deposition could be the major source of PAHs accumulated in leafy vegetables. At watershed scale, Guo et al. (65) demonstrated that wastewater irrigation may lead to the potential accumulation of pollutants and causes corresponding changes in denitrifying communities and denitrification; hence, the potential ecological risk (based on molecular markers for nitrogen cycling) of long-term wastewater irrigation should not be overlooked. In addition to chemicals, antibiotic-resistant bacteria can also be enriched in soil and plants, through the application of sewage sludge to arable land as fertilizer. A long-term field experiment demonstrated that after a 10-year application of sewage sludge in arable land, there was a clear accumulation of antibiotic resistance genes in the soil (66).

To mitigate pollution from the urban environment, holistic and integrated approaches are needed, taking into account the chemical, biophysical, and ecological aspects of the urban system, as well as the social, economic, and cultural contexts of the city. Maintaining and improving the multifunctionality of urban ecosystems, e.g., more efficient waste treatment technologies and infrastructure, incorporating more green and ecological solutions to urban development, an enhanced awareness of the impact of urban consumption, and a change in culture, are called for.

3.3. Land Use

Even though cities are holding the majority of the world's population, urban areas represent less than 1% of the Earth's land cover (67). Compared to the area it occupies, the impact of urban land change is disproportionately large. These impacts occur at a range of scales, from local and regional to global, as a consequence of physical flows of living and nonliving materials, and teleconnections of virtual resources such as finance and ideas (7). Urban land-use change alters local biodiversity and the environment (68), shapes local and global climate by contributing to heat island effects and altered rainfall (69, 70), and drives international trade in agriculture and forestry (71) via teleconnections.

Urban land often grew faster than urban population. In China, such accelerated growth is driven by positive feedbacks between urbanization and economic growth, which causes serious concern over the impact on food production (3). Significant but often neglected land-use change occurs in rural areas, where the aggregated growth of residential land use can be even larger than in cities. With less than half the total population living in rural areas in China, the total residential land use is approximately four times that of urban built-up areas (2).

Understanding urban land-use change requires careful attention not just to the extent and location of change, but to spatial patterns of growth and fragmentation. Urban centers have a tendency to agglomerate, forming urban clusters (72) or urban corridors (73), along which transportation and other forms of development typically occur. Such spatial clusters can act as nodes that influence land-use patterns of entire regions (74). The spatial pattern of such agglomeration can drive environmental outcomes such as urban heat islands (UHIs) (75) and biodiversity (76), as well as air and water pollution as discussed above.

As a consequence of the rapid acceleration of urbanization, and of changes in the locus of drivers from local to distal, there is a gap in our understanding of drivers and spatial outcomes of urban land change in newer urban regions. Older urban settlements with slower rates of growth tend to be compact with relatively predictable patterns of concentric growth, whereas new urban settlements show extensive, nonlinear, and spatially complex patterns of growth and interspersion of rural and urban areas (77). Thus, classical analytical approaches examining land-use change along rural-urban gradients are less applicable in emerging areas of urban growth, especially in the context of the Global South, where urban pockets may be found within rural landscapes and villages within cities (78). The impact of urban land-use change on habitat, environment, and biodiversity in distant rural areas constitutes another area that requires greater study.

There are several spatial gaps in knowledge. China, India, and Nigeria represent the three countries with the fastest rates of urbanization; however, Nigerian urbanization has been relatively less studied, in comparison to research on China and India. In general, we know much less about the patterns of urban expansion in Africa. Other prominent gaps in knowledge are on land-use change in smaller towns, and of de-urbanization in areas with shrinking cities, a phenomenon that has recently gained prominence in parts of Europe and the United States (79).

Predicting and modeling future land-use change resulting from urbanization is essential for sustainability. This has been challenging because of the complexity of understanding and modeling the complex web of local and teleconnected drivers of current urbanization. The influence of macroeconomic drivers on land-use change has increased over time, with actors and spheres of influence increasingly removed from places where changes occur (80). This calls for a shift from place-based and pattern-based research toward a process-based understanding of the drivers of urban land-use change and also for developing a better understanding of how telecoupling and teleconnections drive spatial differentiation (81–83). Frameworks of urban metabolism can play an important role in this regard, helping us understand how material and energy intensity, rates, and patterns of flow can influence efficiency, productivity, resilience, and self-sufficiency, providing important inputs for better urban environmental and ecosystem governance (24). Urbanization and climate change constitute coupled systems in many urban-dominated regions of the world: We also need a better understanding of the feedback loops between these two systems (70, 84).

Finally, what does our current understanding tell us about possible solutions for urban land-use policy? Urban form plays an important role in impacting the environment. Urban compactness may reduce energy consumption and fossil-fuel use for transportation, but it enhances UHI effects and reduces groundwater infiltration; thus, there are trade-offs that need to be carefully considered (85). Smart cities, another approach that is gaining popularity with governments across the world, have grand plans to redesign existing cities via the integration of systems technologies to increase efficiencies of use. They have been critiqued, however, for the lack of democratic participation of people in the planning process, for the dominant role played by foreign private investments, and for exacerbating urban environmental injustices, as observed in numerous smart city projects in India and across Africa (86). In India, the smart cities model tends to focus on the recreational ecosystem services provided by green spaces, water bodies, and other forms of natural land use, while disregarding provisioning ecosystem services such as food, fodder, fish, and fuelwood that are essential for the subsistence, health, and livelihoods of marginalized urban residents such as migrant workers and the urban poor (87). Smart cities have resulted in the exclusion of traditional nature-based communities such as fishers and grazers from lakes, grazing lands and woodlots under private-public partnership programs, further exacerbating social injustice (88).

3.4. Ecosystems

Urban challenges interact dynamically, often in complex ways, to affect urban systems including urban ecosystems (7, 8, 20, 89, 90). Research has shown that cities and urbanization processes modify environments, often causing impaired ecology of urban riparian zones, affecting local and regional climate, and driving losses of native biodiversity and increases in non-native species (91, 92). Urbanization can also exacerbate abiotic stresses such as fragmentation and the suppression of natural disturbances, which hamper the regeneration of the ecosystems through early succession stages. These modifications driven by urbanization, which degrade functions of ecosystems and further increase the impacts of natural hazards and climate change on urban ecosystems, can have reverberating impacts throughout other domains of urban systems. Urban ecosystems are already under general stress from development, pollution, and direct human use (92), and urban expansion into remote inland regions that are often ecologically fragile can present unique challenges that require a contextualized and tailor-made policy measures (93).

In addition to these direct impacts, urban ecosystems are also subject to impacts from complex systems-level interactions (9, 23, 94). Climate change is perhaps one of the most fundamental and more recent drivers of change in urban systems that interacts dynamically with development-driven habitat fragmentation and other human impacts on ecosystems. Urban change includes urban ecosystems and their associated biota (90, 95), which form the foundation upon which social and technical-infrastructure systems are built, developed, and organized. Almost all of the impacts of climate change have direct or indirect consequences for urban ecosystems, biodiversity, and the critical ecosystem services they provide for human health and well-being in cities (92). Research has shown that urban ecosystems are rich in biodiversity and provide critical natural capital for climate change adaptation and mitigation, and yet these natural systems are being significantly affected by climate change and urbanization (84, 96). Expanding research on urban ecosystems and various types of green infrastructure such as bioswales, green roofs, and parks have an important role to play in adapting to climate change in cities (97).

In a comprehensive review of the potential impacts of climate change on urban biodiversity in London, Wilby & Perry (98) highlight the importance of four threats to the biodiversity in the city: competition from non-native species, pressure on salt marsh habitats from rising sea levels, drought effects on wetlands, and changing phenology of multiple species as earlier springs occur more frequently (99). For example, the changing dynamics of UHI in cities can change the reproductive and population dynamics of animals. Insect life cycles and migration patterns changing in response to urban warming has been well documented (100). Butterfly species in Ohio appear to have shifted when they fly in response to urban warming. Some native butterfly species appear to be at increased risk due to the shortening of their flight periods (101).

Climate change is shifting species ranges and in some cases causing negative impacts on urban forests with its associated insect pests, which prey on susceptible and already stressed urban trees. Urban trees experience many forms of stress, including heat stress, air pollution, low air humidity, and soil drought. Rapid climate change can have a significant impact on the distribution and biology of trees. In Philadelphia, climate change is already influencing the biology of urban tree pathogens and pests. Results from a recent study indicate that the future climate in Philadelphia will become less optimal for multiple tree species, given major pests and diseases are likely to become more problematic (49).

Ecologists tend to discuss risks to ecosystems in terms of disturbance (see, e.g., 102, 103), which can be applied to urban systems (22). Variation and extremes in weather and climate and other disturbances have always been part of the functioning of natural ecosystems and provide a wide range of benefits such as soil fertilization in floodplains in the case of floods or groundwater recharge in the case of intense precipitation events associated, for instance, with typhoons. However, major impacts on the ecosystem might occur if hazards affect a degraded and less diverse ecosystem, as is often the case in and around cities (104). This could translate to a temporary or even permanent decline or impairment in supplying critical ecosystem services to urban and periurban areas. Mitigating and adapting to climate change and urbanization in urban regions thus needs to take into account the effects of the built-up infrastructures and climate change on the ecological or biophysical components of local and regional ecosystems.

Projecting impacts of climate change on the distribution of species is complex with many factors to consider, including dispersal ability, species interactions, and evolutionary changes (105, 106). Still, future climate change in cities, when combined with additional urban stressors such as short-lived climate pollutants, land-use change, and direct human impacts are expected to pose difficult challenges for urban species and ecosystems. Maintaining adequate levels of biodiversity and managing urban ecosystems to ensure resilient supply of critical ecosystem services necessary for supporting needs of expanding urban populations may become increasingly challenging in the future as climate change intensifies effects on cities. Which ecosystems will be most affected in the near and longer term future may be signaled by current species responses to climate change (100, 107). The risks and vulnerabilities associated with urbanization and climate change in urban ecosystems are likely to vary with temporal and spatial scale as well as the nature of change (e.g., chronic versus acute), although in general they are expected to increase over the next several decades (84).

Despite significant challenges facing urban ecosystems, biodiversity, and the important ecosystems services they provide, nature in the city is a critical part of solutions to local and global environmental challenges (108). For example, ecosystems are beginning to form a key component of climate change adaptation (CCA) and disaster and risk reduction (DRR) as “nature-based solutions.”

Initial research and practice has shown that well-managed ecosystems can contribute to the reduction of climate change risk and are very often cost-effective, multifunctional, and win-win solutions especially in the long run (109). In developing countries ecosystems provide an important source of livelihood for local communities (108, 109). In addition to useful strategies for CCA and DRR, green and blue infrastructure provide multiple cobenefits such as recreation, psychological well-being, and pollution control opportunities (110). These are also often flexible and applicable in a variety of settings (111).

It is increasingly clear that ecosystem-based strategies can be cost effective. In Portland, Oregon, an increase in street trees has been estimated to be three to six times more effective in managing storm water per $1,000 invested than conventional drainage systems. These estimates made Portland inclined to invest $8 million in green infrastructure in order to save $250 million in hard infrastructure costs (112). For some urban challenges, such as the UHI effect, urban cooling by green spaces can be significant. Wong & Yu (113) estimated 3.07°C as a mean value for cooling by vegetation in Singapore, whereas the UHI of the city reaches 7°C (114). In Bangalore, street trees can reduce afternoon ambient air temperature by 5.6°C, and road surface temperature by as much as 27.5°C (115). However, green infrastructures generally require large amounts of land to deliver ecosystem services, and land is often in short supply in many built-up urban areas.

There is increasing evidence that hybrid approaches (23) provide cost-effective hazard protection solutions. In Hamilton City, California, and in its surrounding rural areas exposed to floods, the option of setback levees, facilitating the natural functioning of the floodplain, was estimated to be a more cost-effective strategy when compared to upgrading existing levees (116).

Nature-based approaches to dealing with climate change in cities explicitly recognize the critical role of urban and periurban ecosystem services, which require thoughtful management to sustainably supply these services to residents who need them over the next 20, 50, and 100 years. Ecosystem-based planning can strengthen the linkages between urban, periurban, and rural ecosystems through planning and management for nature-based solutions at both city and regional scales.

3.5. Solid Waste Management

Cities are increasingly challenged by the problems of growing waste. As the by-product of urban lifestyle, the amount of municipal solid waste (MSW) is growing much faster than the rate of urbanization. In 2012, 3 billion urban residents worldwide generated approximately 1.3 billion tons of waste (that is 1.2 kg per person per day—almost doubled since 2000) (117). In Beijing, for example, the total volume of MSW has increased almost six times between 1980 and 2014, whereas per capita generation has increased almost 50% (118). Industrialization and economic growth both contributed to the growth in waste. However, recent efforts to "decouple the waste from the wealth" has led to the lower generation of waste per unit of GDP in some countries, which demonstrates the window of opportunity for cities to find better solutions for this fundamental public service of modern cities (119).

The volume and composition of waste has changed over time and varied from place to place due to different lifestyles, leading to a variety of waste management practices throughout human history (120). Before industrialization, waste was generally not a public issue given insignificant amounts and easy disposal. Sustained urban growth along with industrialization increased the volume of waste in the cities with large populations, resulting in the rapid deterioration in urban environmental health and sanitation. This necessitated the establishment of a municipal authority with waste removal powers and the modernization of the waste management system for proper disposal. With an emphasis on economic efficiency in the market approach to waste management, the system steadily moved toward the profitable option of incineration with energy recovery, rather than the recycling of materials or waste reduction at the source (121). Such a trend significantly undermines the once important role of the informal sector in solid waste recycling in developing countries, although recent evidence suggests they are still playing a significant role in the collection, processing, and trading of recyclable materials in cities (122), with multiple stakeholders playing various roles in the process (123).

Since the 1990s, the increasing demand for waste disposal, the rise of the NIMBY (not in my back yard) syndrome in public opinion, and the shortage of land for landfills in cities has called for alternative strategies to solve the problem (124). However, the drivers for waste management are different between the developed and developing countries. Public health, local environmental protection, and resource value are still key drivers for recycling in developing countries (125), whereas in developed countries and some rapidly developing countries, the focus is increasingly shifting toward climate change and the closed-loop concept through holistic resource management (126).

Data for municipal wastes vary significantly due to inconsistent statistics and definitions in different countries. In general, MSW constitutes ~14–20% of all wastes generated worldwide, with per capita generation varying from more than 5.3 kg/day for OECD (the Organisation for Economic Co-operation and Development) countries to less than 0.8 kg/day in developing countries in 2014. Changing life styles, ineffective policies, and lack of awareness in developing countries may increase the latter exponentially over the next decade. Much of the wastes generated worldwide (57 to 85%) were primarily disposed in landfills, including open and engineered landfills (127).

Serious environmental issues are predicted if the growing MSW is dumped without proper separation and disposal, including contamination of land and water bodies due to discharge of leachate hazardous materials, air pollution due to emissions from burning and release of methane from anaerobic decomposition, and risks to human health and spreading of disease in areas near landfill sites.

The environmental issue related to urban waste management has transcended beyond local concerns due to its contribution to climate change, and there are many studies attempting to quantify the linkage between solid waste and greenhouse gas (GHG) emissions (128). The IPCC estimates that solid waste management accounted for approximately 3% of global GHG emissions in 2010 with most of that attributable to methane emissions from landfill sites (129). However, the IPCC estimate does not account for savings achieved through recycling. Using a life-cycle approach, a study estimated that a 10 to 15% reduction in global GHG emissions could be achieved through landfill mitigation and diversion, energy from waste, recycling, and other types of improved solid waste management, and including waste prevention could potentially increase this contribution to 15 to 20% (127).

Recycling contributes to preserving renewable resources such as metals, plastic, glass, as well as nutrient resources for soil from organic waste, and it consequently decreases the amount of pollutants being discharged into the environment. It depends on a comprehensive solid waste resource management strategy to fulfill this target by increasing recycling and composting and reducing the waste sent to landfills and incinerators. Efforts that only target the end stage of the product life cycle at the point of waste disposal are not enough. A growing emphasis has been put on the very beginning stage of the product design to incorporate elements of waste reduction and recycling (130).

In general, discussions of the urban waste issue have been increasingly moved beyond a focus on technical solutions for the disposal of physical detritus at the final stage. Increasingly, critics have been targeting the mode of mass production and consumption, as well as the consumer culture related to it.

As a cross-cutting issue impacting on many aspects of society and the economy, urban waste management has strong linkages to a range of other challenges in urban governance, such as health, climate change, poverty reduction, food and resource security and land resources management. To achieve comprehensive and proper management of MSW, there is a clear need for a multi-stakeholder partnership working toward holistic and effective management in all stages, especially, reforming the economic system into a mode of sustainable production and consumption (131). This includes questioning the normative underpinnings of the current growth model (132). The decoupling of waste and wealth requires substantial transition in the value and consumer behavior, new policy instruments, and effective institutional design that allows and implements technical and conceptual innovations, as well as a different measurement of economic performance.

A growing collection of policy tools are emerging to promote the circular economy that encourages the 3Rs—reduce, reuse, and recycling—at the society level and to involve multiple stakeholders at every stage of the waste stream to tackle with the complexity, costs, and coordination toward an integrated approach to waste management. There seems to be a gap, however, between household willingness and readiness to engage and the policies that are in place. For example, a study in African cities shows that up to 80% of households would support source separation policies (133).

The waste management system requires more flexibility to incorporate innovations in this sector. Some policy tools around the concept of product service system or urban symbiosis are emerging to stimulate innovations at different stages of the product life cycle (134, 135). Various economic instruments are applied to provide the incentives for such innovation; however, the transaction costs for regulations blur the real effects (136). The principle of extended producer responsibility provides an alternative pathway to waste reduction by empowering the producers to reshape the whole product-service chain, which raises new debates on the boundary of responsibility between municipalities' waste management systems and the producer organizations (137).

Waste is an inextricable mix of social, economic, and environmental attributes. With the increasing power of consumers in society, the role of social norms and values has been increasingly recognized in pursuing inclusivity and environmental justice in the waste management sector. The use of community-oriented tools toward a "Zero-Waste City" could be highly effective (138–140).

3.6. Climate

The linkages between urbanization and climate are multifaceted and span multiple scales. Here we examine several aspects of such linkages.

3.6.1. Urbanization and physical processes. Urbanization leads to a transformed landscape and changes to the physical properties and morphology of the surface, the composition and dynamics of the atmosphere, and the way that water is stored and routed. The changes in form and function that arise as a consequence of urbanization are profound: The physical properties and morphology of the surface are altered; the atmospheric composition and dynamics are changed along with the way that water is stored and routed through the landscape. These changes, in turn, affect the climate within the city and can also modify the climate of the surrounding regions (141). A recent study conducted in the Beijing-Tianjin-Hebei metropolitan area suggests that urbanization leads to an increased surface temperature, reduced annual mean water vapor mixing ratio and wind speed, and increased convective precipitation (142). The links between these changes and those physical processes and variables that influence the local urban and, depending on the size of the city, the surrounding regional climate, are summarized schematically in **Figure 2**.

Several clear links between urbanization and climate in cities can be noted, including radiation and energy budget, water and carbon budgets, and urban turbulence (145). In urban areas, there is an increased diffuse, and reduced total, incoming shortwave (solar) radiation at the surface (146), but increased "trapping" of the incoming shortwave radiation in urban canyons due to warmer and more polluted urban air (143, 147), as well as the heat emitted from urban industrial processes and heating systems (148). The enhanced urban run-off due to increased impervious surfaces leads to reduced evaporation and transpiration (149, 150), whereas vegetation cover in suburban areas often contributes to significant evaporative heat losses. Increasing urban greenspace therefore provides a means to passively modulate urban heating (151) and enhance the uptake of carbon dioxide (152, 153). Recent research in Phoenix suggests that in addition to vegetation cover and surface materials, urban form and spatial arrangements of urban features can have significant impacts on local microclimate (154). The presence of inflexible, impermeable, sharp-edged buildings in cities changes the airflow and microclimate, resulting in highly variable and gusty winds at times but, depending on the layout of the buildings and streets and trees, these canyons can also be very calm. This affects the transport of pollutants, dust, and heat (155) and is a key factor affecting the overall climate of cities.

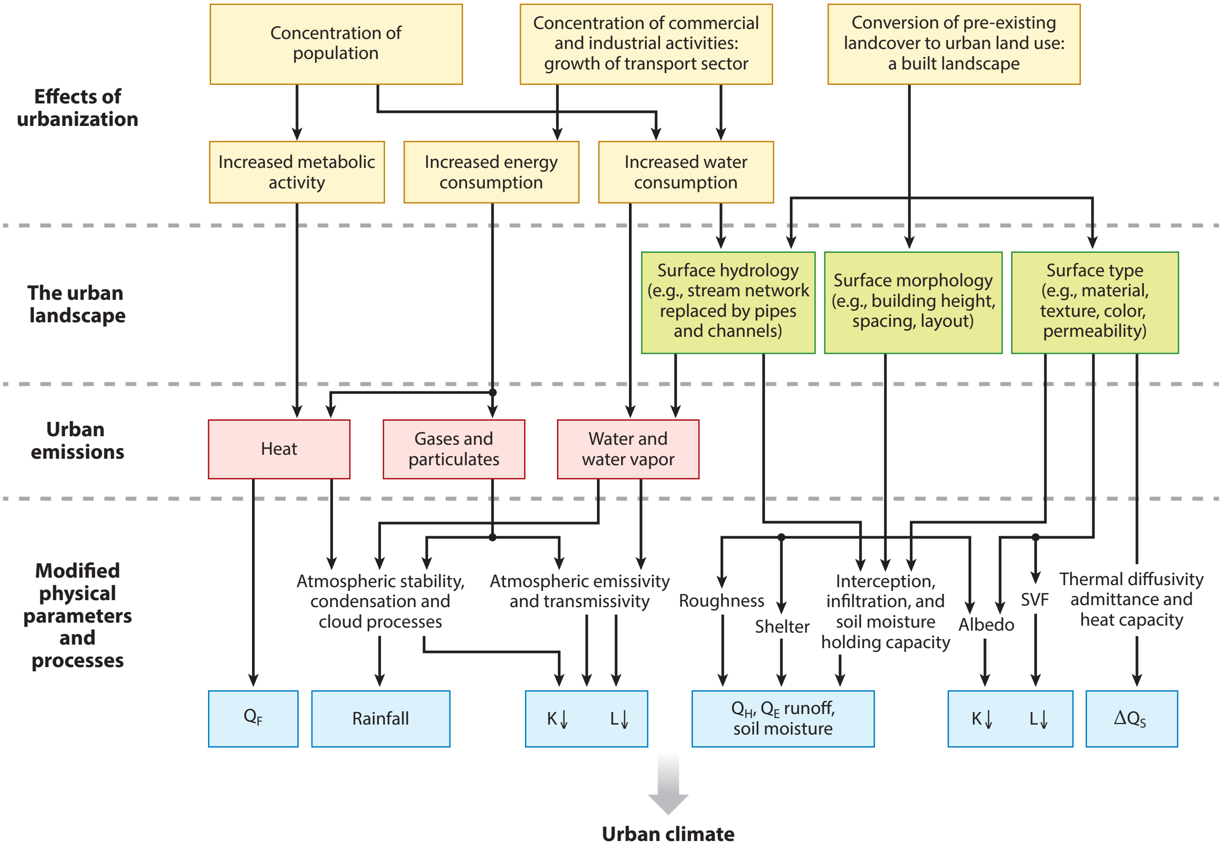

Figure 2

Physical processes that affect urban and regional climate. These links have been clearly established via theoretical, measurement and modeling studies over the past three decades (141, 143, 144). Symbols: Q_F, Q_E, Q_H, ΔQ_S: fluxes of anthropogenic heat, latent heat, convective and stored heat, respectively; K↓ and L↓: downwelling shortwave and longwave radiation; K↑ and L↑: reflected shortwave and emitted longwave radiation. Figure modified from figure 3.1 in Reference 145.

3.6.2. Cities, weather, and climate. Urban climate change projections for both temperature and precipitation show wide variation in cities around the world, with temperature generally increasing and precipitation both increasing and decreasing depending on location (96). Distinct urban climate has been observed in settlements with as few as 4,500 inhabitants through to the world's largest megacities (145).

The classic UHI refers to observations of near-surface air temperature within and outside an urban area, which show increased air temperatures near the ground relative to the surrounding countryside and whose causes lie in different cooling rates (143, 156–158). The strength of this classic UHI (i.e., relative warmth compared to the surrounding nonurban landscape) varies with population, building density, the relative fraction of built surfaces, the season (the UHI is found to be stronger in the dry season in the subtropics and tropics), and latitude (weaker at lower latitudes). Urban form is also found to be closely linked to the number of extreme heat events in large US cities, with sprawling metropolitan regions experiencing more increases than more compact cities (159).

Cities are typically more sheltered—i.e., average wind speeds are reduced in the overlying urban atmosphere—when regional winds are of moderate strength. However, both the level of turbulence and the mean wind strength can be increased within the urban canopy (as noted above). Cleugh & Grimmond (145) summarize the complex nature of the mean and turbulent airflow field within urban canyons. Cities have also been shown to create their own localized thermal circulation pattern under calm regional conditions, centered near the warmer urban city core (160).

Cities have the potential to affect rainfall because of changes in urban atmospheric dynamics, changes in the microphysical mechanisms associated with cloud and rainfall development, and by providing additional moisture sources through urban industrial processes. Under light synoptic winds, the warmer city can initiate moist deep convection (161, 162) and convective thunderstorms (163), as demonstrated through model simulations and observations. Cities have also been observed to modify the tracks of storms and frontal systems as they pass over the urban area (163). Aerosols from human activities can grow into cloud condensation nuclei and modify the growth of cloud and rain droplets (164). Observations have confirmed the hypothesis that urbanization may lead to increased precipitation downwind of cities (165). Urbanization is found to affect the regional rainfall patterns and extremes in India (166). Shi et al. (70) show that urbanization and air pollution are likely the main contributors to the spatiotemporal distribution of heavy rainfall in China over the past six decades.

3.6.3. Implications. In creating their own distinctive and measureable climate, cities provide a tangible demonstration that human activities can modify climate and are therefore an analog for studying global anthropogenic climate change caused by increasing levels of GHGs in the atmosphere.

That researchers have been able to observe, explain, and simulate a characteristic urban climate—at the microscale (within the city), in the overlying atmosphere, and regionally for an entire city—has important implications. It means that urban warming will be superimposed on a long-term trend of increasing global and regional temperatures, including heat extremes. The reduced diurnal temperature range and elevated night-time minimum temperatures of cities (amplifying global warming trends), along with humidity, will exacerbate the impacts for vulnerable sections of urban communities. Similarly, changes in the intensity and frequency of rainfall, storms, and air pollution events, which have been observed in cities, will be superimposed on changes in extreme rainfall, drought frequency and intensity, extreme fire weather, and increased heat extremes that are associated with global climate change.

Cities are therefore an amplifier of global climate change, which is of great relevance to climate adaptation strategies. But because the processes result from changes in city form and function, urban climate can be managed through climate-sensitive urban design (159). Climate mitigation goals can also be addressed by integrating the principles of climate-sensitive and water-sensitive urban design—through the passive microclimate modulating role of urban vegetation (167).

4. EMERGING TRENDS AND REMAINING QUESTIONS

Several observations can be drawn on the basis of recent research trends and findings on urbanization and environmental change.

- Although rapid urban population growth is most commonly highlighted, recent studies suggest that the associated growth in environmental impacts is often larger and/or faster, as manifested in land-use change, waste generation, and air and water pollution, among others. Such an amplified and/or accelerated tendency in urbanization-environmental linkages deserves more research attention.

- The magnitude and distribution pattern of environmental impacts tend to be diverse and varying along the urban-rural gradient or across different urban regions, suggesting that the local social, economic, and natural contexts play important roles in shaping the impacts. The implications are twofold: More in-depth place-specific studies as well as comparative analysis across places are needed to achieve comprehensive understanding and a tailored approach in forming urban- and regional-level planning and management policies is needed.
- Research focus is increasingly shifting from understanding and quantifying the environmental impacts of urbanization to understanding the drivers and mechanisms that shape such impacts, and from identifying patterns to understanding the processes. There are earlier studies emphasizing the importance of understanding the process and mechanism behind environmental change (82, 168). Hence, this trend is perhaps more of a convergence of approaches rather than an advent of a completely new one.
- Increasing evidence highlights the strong and complex interactions and interlinkages among different environmental processes, e.g., between climate change and ecosystem change in urban areas, between economic growth and urban land-use change, between urban climate and air pollution, between environmental and social, economic, cultural processes as demonstrated in the waste management sector, and between environmental outcomes and local and regional planning and management processes as demonstrated in ecosystems, air and water pollution, and climate sections above. Exploring interlinkages among multiple processes, which is not common due to its complexity, will be essential to inform a truly systems approach in urban policy and practice.
- Recent literature shows some important conceptual advances in understanding cities as human-dominant, complex systems with multiple actors, structures, processes, functions, and interlinkages both within and beyond cities. Although each has a distinct focus and disciplinary starting point, all are pointing to the need for a more integrated systems approach taking into account a longer and broader temporal and spatial scale.

5. GOVERNING THE URBAN-ENVIRONMENT LINKAGES

Addressing urban challenges and harnessing opportunities of urbanization both require good governance (169, 170). National government has a role to play in urban governance, given that national policy can play a significant role in shaping the urbanization trajectory and outcome (2, 3). As illustrated above, almost all the challenges discussed so far point to the need for improved urban planning and management practices. Environmental management in most cases is part of the urban governance portfolio, but the focus tends to be within the urban administrative boundaries, and there are inherent spatial-, temporal-, and administrative-scale issues in terms of integrating regional and global environmental concerns into urban management (171, 172). In addition, despite the growing evidence on the close association between environmental emissions or urban microclimate and urban form, structure, or land-use planning (173, 174), such connections are not always reflected in the planning and management practice. Understanding the complexity and the multiple connections within a city can help urban planners and practitioners deliver better outcomes (175). A study conducted in Finland found that most urban planners and sustainability professionals could not see the links between urban structure and sustainable life-style choices (158, 176).

There is a clear shift in urban policy and governance toward a more people-centered approach, shifting away from focusing only on economic growth, and with enhanced public participation, and coproduction of knowledge with stakeholders (2, 177, 178). The growing challenge of climate adaptation and urban disaster and risk reduction calls for an adaptive governance that goes beyond the notion of adaptation planning, emphasizing improved governance, processes, and tools (179). A large number of new concepts emerged, e.g., smart city, eco-city, low-carbon city, with many of them closely linked to a specific city's aspirational goal, and to some extent to the actual urban practices. To what extent these new concepts are delivering tangible results is not clear yet. Research exploring the notion of urban sustainability experiments highlights the importance of building up transferable knowledge and intercity learning (13).

6. CONCLUSION

Urbanization has been, and will continue to be, one of the biggest societal transformations. Although urban challenges are far from being successfully resolved, the potential for urbanization as an opportunity and cities as a context to provide solutions is increasingly recognized by research and policy processes alike. Recent years have seen some significant conceptual and empirical advances in urban-environmental linkages. There are several emerging trends and remaining questions in urban environmental research, including (*a*) increasing evidence of the amplified or accelerated environmental impacts of urbanization; (*b*) varying distribution patterns of impacts along geographical and other socio-economic gradients; (*c*) a shifting focus from understanding and quantifying the impacts of urbanization toward understanding the processes and underlying mechanisms; (*d*) an increasing focus on understanding complex interactions and interlinkages among different environmental, social, economic, and cultural processes; and (*e*) conceptual advances that articulate systems approaches in cities. Public participation and coproduction of knowledge with stakeholders become increasingly important in finding solutions toward sustainable cities. Under a plethora of guiding concepts, each manifesting the specific aspirational goals and visions, many cities in the world are actively experimenting toward sustainability.

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