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Ecological science and transformation to the sustainable city

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ABSTRACT

There is growing urgency to enhance the sustainability of existing and emerging cities. The science of ecology, especially as it interacts with disciplines in the social sciences and urban design, has contributions to make to the sustainable transformation of urban systems. Not all possible urban transformations may lead toward sustainability. Ecological science helps identify components of resilience that can favor transformations that are more sustainable. To summarize the dynamics and choices involved in sustainable transformations, a "metacity" framework is presented, embracing ecological processes in cities as complementary to those involving society, power, and economy.

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Introduction

Contributing to the sustainability of the biosphere through facilitating the societal dialog about Earth's future is an urgent priority for researchers (Chapin et al., 2009, 2011; Clark, 2007; Odum & Odum, 2001). The rubric of sustainability suggests an engagement across disciplines and with society, with the larger goal of improving both human well-being and the resilience of the Earth's biological foundations on which humans depend and constantly interact. Nowhere is this double commitment more needed than in the growing urban realm (Pickett, Cadenasso, & Grove, 2004; Pincetl, 2012; Sassen & Dotan, 2011). It is crucial to explore how urbanization, as one of the major contributors to global change (Vitousek, Mooney, Lubchenco, & Melillo, 1997), might be better directed toward improving the sustainability of the Earth's biosphere. However, global urbanization is not simply a conversion of wild, pastoral, or agricultural land to city and suburban cover. Urbanization also involves radical changes in the form, metabolism, economy, and demography of urban ecosystems themselves. We label such radical changes as urban transformations. Past examples of urban transformations include the fundamental restructuring of English settlements by the industrial revolution, or the conversion of Chicago from a fur trading center to a major subcontinental rail and meat processing hub. Our approach also recognizes that these urban transformations are embedded in broader socio-ecological processes that transform rural lands and livelihoods as well (Williams, 1975).

We draw on biological ecology, social sciences, and urban design to examine a variety of possible urban transformations and the ways in which such transformations might support or inhibit urban sustainability. A shift in the form and dynamics of urban areas toward sustainability would indeed be a radical and, we assume, positive transformation (Curwell, Deakin, & Symes, 2005). This paper presents three themes: (1) the diversity of urbanization around the globe can identify inflection points in the trajectories of urban change where ecology can contribute, (2) there are many actual and potential transformations that cities can undergo, and (3) a social–ecological-design vision can help move cities toward sustainability through the processes of resilience. These three themes are developed through the following steps. First we provide a brief overview of the global trends in urbanization that set the context for understanding urban transformations, which are triggered by both crises and opportunities that open the way for enhanced urban sustainability. Second, we examine how ecological processes might contribute to urban sustainability and may help favor this transformation among the many possible trajectories of urban change. Third, we develop a framework that accounts for the variety of urban forms now emerging around the globe, in order to promote the interdisciplinary work needed to support sustainable urban transitions. This analysis is intended to better inform choice among the possible courses of action aimed at increasing urban sustainability.

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The global urban tide: the context for urban transformations

Urban lands exhibit a wide variety of forms around the world. Even within regions they span diverse kinds of fabrics, from traditional north temperate mosaics encompassing city centers to sparse exurbs, while in the Global South, city form often includes informal settlements such as slums, favelas, and shantytowns (Fig. 1). This spectrum of urban areas is already home to more than half of the world's population, and according to the United Nations, will accommodate more than 80% of all people in but a few decades. This remarkable urban tide is driven by population increase and migration, as well as by the less visible requirements of global institutions and finance (Sassen, 2001). The world population is projected to add three billion people before stabilizing at around 10 billion in the coming decades. This increase is equivalent to the number of new urban residents projected over that same time period (United Nations Population Fund, 2007). Effectively all new people on the planet will be urbanites, and most will be living in developing countries.

People are drawn to cities by the perceived amenities they provide, such as the promise of jobs, the access to education, or the desire for a healthier and easier life (Glaeser, 2011). For many, cities are the only option, as environmental hazards, conflict, and reduced access to traditional livelihoods make rural life ways untenable. Many governments have tried to halt the urban tide, often by outlawing urban migration outright or by declining to provide services for residents of unauthorized or impromptu urban settlements (United Nations Population Fund, 2007). Still the tide continues (Fig. 2).

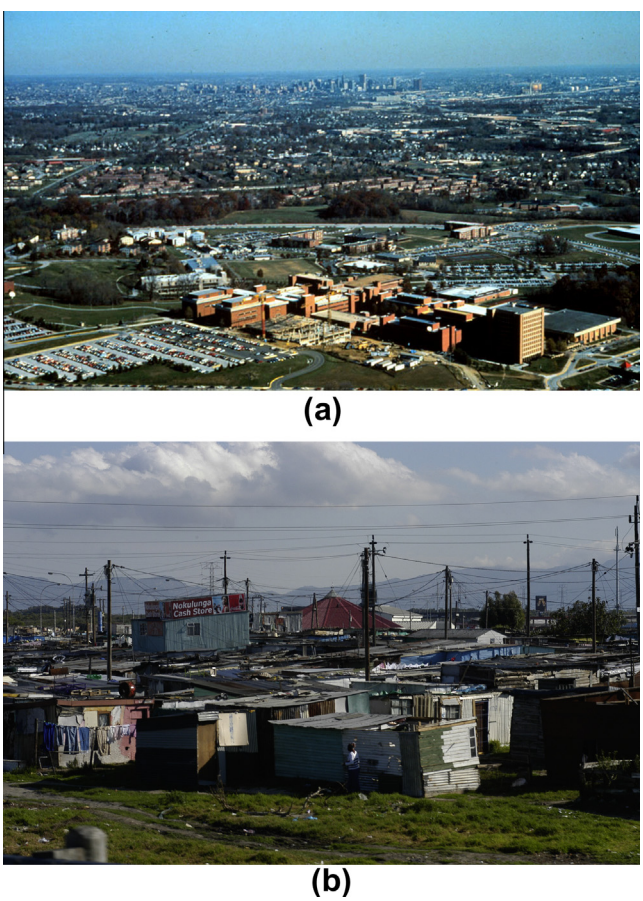

Fig. 1. Two contrasting examples of global urban form. Left panel: an oblique aerial view of Baltimore, MD, US, representing a post-industrial city. Right panel: an informal settlement in Cape Town, South Africa illustrating an increasingly common element of rapidly growing cities. Photo A courtesy of UMBC; Photo B, (c.) S.T.A. Pickett.

How will cities differ in the future? First of all, the sheer number of cities will increase. Such increase includes cities established *de novo*. Second, the maximum size of cities will continue to increase. The United Nations (2007) calls cities with more than 20 million residents "metacities" or "hypercities." These coinages reflect "city inflation," since in the past the largest category of cities was the "megacity," which exceeded a mere 10 million people. In spite of the growth of the largest cities, the majority of urban growth will occur in medium-sized cities that have from 500,000 to 1 million people (United Nations Population Fund, 2007). This is not necessarily a good thing, as smaller cities in the Global South may not have the resources to provide healthy, well-functioning systems. However, smaller cities are likely less "path dependent" and carry less inertia of fixed investments (Childers, Pickett, Grove, Ogden, & Whitmer, 2013; Ernstson et al., 2010). It is such intermediate sized cities that may be better poised to employ new, more sustainable ideas (Childers et al., 2013). In other words, small to medium sized cities may "leap-frog" traditional urban structures and functions to advance more effectively along sustainable trajectories.

As cities grow in extent and size, simple views of cities are less useful. Classically, cities have been conceived as having a dense core, in which most non-residential functions are concentrated, surrounded by rings of less and less dense residential and minor commercial or manufacturing functions. In the industrialized world today, the density profiles of urban areas are flattening as they spread. That is, urban mosaics of commerce, industry, residence, and transportation extend farther into the countryside while old city centers thin. Furthermore, the business, commercial, and industrial functions that were once the purview of the central city have been dispersed broadly, and are now served by sprawling highway networks in peri-urban areas (Garreau, 1991; United Nations, 2007). Even in the Global South, the human connections between city cores and distant settlements generate urban-like rural areas (McHale, Bunn, Pickett, & Twine, 2013). Moreover, globalization has engendered new forms of political and economic governance, resulting in unprecedented urban global interdependency and connection (Sassen, 2001).

Crisis versus opportunity: crucible of transformation

These staggering facts, figures, and projections can be read as a distress signal. However, a more positive perspective is possible. The current state of urbanization presents the opportunity for transformation. The science of ecology has contributions to make toward goals of urban sustainability through understanding and helping design and manage existing and emerging cities (McGrath et al., 2007; Spirn, 2001). To make such contributions, it is necessary to understand the kinds of transformations that cities can experience. What can be learned from past transitions which can promote future urban transformations that are better informed by sustainability? Understanding urban transformation also requires an articulation of what systems are transforming *from*. We identify these below as city modes. Potential transitions between different city modes represent inflection points – the periods or places where urban change can be turned in more resilient directions to support sustainability goals. These inflections are also situations where ecological information can be especially helpful.

A classical model of urbanization links the evolution of cities with industrialization. This model, based on the experience of cities in the Global North, starts with cities as mercantile settlements, fueled by craft and trade. The second phase of urban development was stimulated by industrialization. As industry was introduced and grew, city population increased to staff the factories, and the economy shifted to focus on the concentration and conversion of

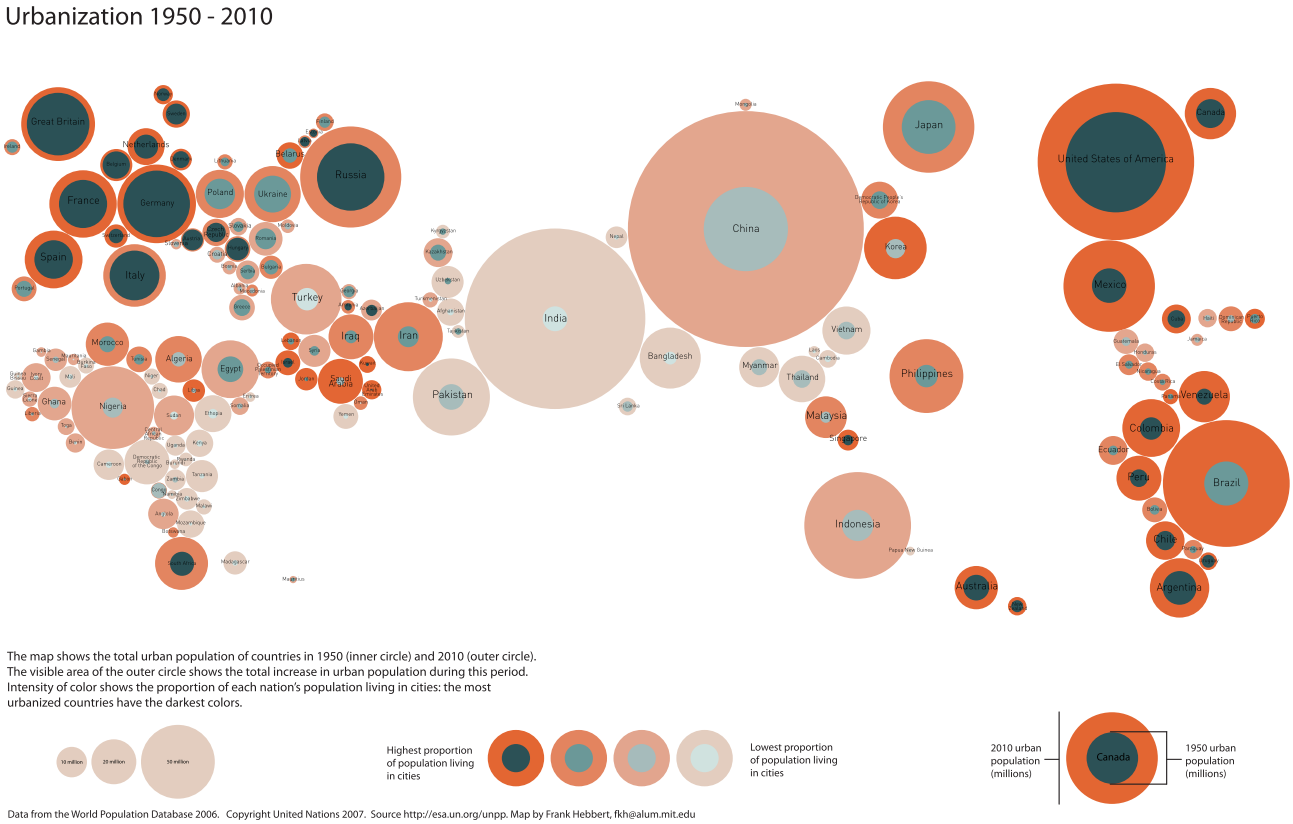

Fig. 2. Global differentials in past and projected urbanization, based on data of the United Nations World Population Database of 2006. Map by Frank Hebbert, formerly of the MIT Department of Urban Studies and Planning. Used by permission.

raw materials into consumer goods and accumulated wealth (Boone & Modarres, 2006; Olson, 1997). Such industrial cities were productive but also highly polluted, disease ridden, and unhealthful. In the Global North, Progressive social agendas and modernist cultural programs emerged in the late 1800s to solve these problems. Ultimately, a less damaging form of the industrial city emerged, which was labeled the *sanitary city* by environmental historian Martin Melosi (2000). Provision of clean water, sanitation, public education, recreational facilities, and green space along with establishment of public and non-governmental institutions to integrate new migrants into the social fabric are aspects of the sanitary city. Many of these investments came, over time, to represent a source of inertia thwarting further evolution of the sanitary city (Childers et al., 2013).

This model of urban transformation from the industrial city to the sanitary city is associated with a human demographic transition (Boone & Modarres, 2006). Simply put, as people move from agricultural settlements having little access to health and educational services, to urban areas where the economy is primarily industrial, major shifts in their demographics occur, from high to low birth and death rates. Improved health care and reduced infant mortality ultimately lead to reduced family size. Increased education and literacy, particularly as it relates to empowerment of women, also contributes to the shift.

Although there are key features of the sanitary city that clearly contribute to this classic demographic transition, social scientists have found the combined demographic transition and urbanization model wanting (Boone & Modarres, 2006). Far from being a deterministic, universal trajectory, it is at best a special case. There are cities throughout the world where the assumptions behind the demographic transition do not hold. For example, people may concentrate in cities for reasons other than the availability of industrial jobs. Furthermore, the sanitary infrastructure and services characteristic of Northern European and North American industrial cities may not emerge fast enough to match the explosive growth of new cities elsewhere. In addition, cities in the Global South are enmeshed in a global economic system where the benefits of urban industrialization, such as the capital needed to finance the amenities of the sanitary city, accrue elsewhere. Even in the Global North, the benefits of the sanitary city are unevenly distributed. In other words, the sanitary needs of urban dwellers in many situations may be difficult to fill.

This disconnect between the motivations for urbanization and the amenities achieved alerts us to a multitude of drivers for city growth. Cities may grow due to perception of opportunity, rather than real availability of jobs and resources. They may spring up or expand by the arrival of vast refugee populations. In the contemporary, highly connected world where cell phones and the Internet spread visions of luxurious lifestyles into the bush and the boonies, city populations may swell by a flotilla of hopeful consumers. Of course, the individual and household choices mentioned above can be promoted or constrained by government policy. For example, city growth can occur as a result of policy and government fiat in centrally planned countries.

City Modes and urban transformations: from what to what?

The different drivers of urbanization, enumerated above, identify contrasting *city modes*. While there may be a generalizable spatial form associated with some of them, it is not primarily the form of the urban fabric that we wish to emphasize in identifying urban modes. It is rather the answer to the question, what are cities *for*? We can expand on this simple question: Why is it that people and institutions move to urban areas or choose to stay in them? What

things do they wish to accomplish in their new or changing urban settings? What benefits do they imagine to accrue to city life? The answers can be quite diverse: Cities can be for processing of commodities, for transfer between different transport modes, for the protection of a civilian or refugee population, for the concentration of religious power, for hosting government, for facilitating consumer activity, for manufacturing things, for generating wealth, for enhancing social identities, for stimulating innovation, for focusing education, for promoting sustainability, and a host of other goals. This list is intended to be an illustrative, but not exhaustive, roster of city modes. Of course, even a single city is generally "for" different things. Such differentiation of urban modes can depend on where in the urban area one focuses, or what social group or other human institution is of interest. City modes are therefore not absolute, and more than one mode can coexist in a conurbation. City modes can change through time, as the transition from industrial cities of production to sanitary cities suggests.

The multitude of modes suggests a plethora of possible urban transformations (Fig. 3). The mode of a settlement at a particular period can change to another mode at a later time. For example, a refugee settlement can, if it persists and resources are available, transition to a sanitary mode. Ideally, refugee settlements would transition to sustainable settlements, in which people's needs for sanitation are met without locking in some of the undesirable features of classical sanitary cities, to be discussed later. Settlements organized to promote the marketing of regional commodities may shift to cities of luxury consumption based on the growth and wealth of their populations. Of course, not all transformations are equally desirable for either human well-being or for ecological resilience. For example, sanitary cities may, upon loss of population, political power, and financial resources, become less able to protect the health and well-being of their residents. Many shrinking, post-industrial cities are facing such a retrogressive transition (Bontje, 2004), with the burdens falling first and most heavily on the disadvantaged.

Of the many possible transitions, the aim to enhance sustainability stands out. Social scientists, ecologists, urban designers, and social activists point to increased sustainability as the most desirable transformation for contemporary cities (Childers et al., 2013; Grove, 2009; Naess, 2001; Pickett, Cadenasso, & McGrath, 2012; Pincetl, 2012). Indeed, many municipal governments and associations of governments have adopted sustainability as a goal (Bai, Roberts, & Chen, 2010; Beatley, 2000; Curwell et al., 2005; Jenks & Jones, 2010). Baltimore City's sustainability plan is a good example (Fig. 4), especially given its basis in a broadly inclusive community process (Baltimore City, 2009). However, as has been demonstrated by the critique of the modernist model of urban and industrial development, no transition is guaranteed. This raises the issue of how to promote the transition to sustainability, regardless of the starting predominant city mode, or even for cities originating *de novo*.

The sustainable city as a social goal: resilience as a tool for transformation

Sustainability has two key features. One is a concern with intergenerational equity and equity among contemporary peoples empowered to different degrees. Second is a joint concern not only with social and economic processes, but also with environmental processes. Hence, sustainability is considered to be built upon three pillars: Sustainable places are those that succeed in supporting resilient ecological, social, and economic processes. Sustainability is a normative social goal, resulting from a civic dialog, and suggesting processes of change toward that goal.

Strictly speaking, no city is sustainable in the sense of being an autotrophic or even self-supporting ecosystem. Cities will always be heterotrophic: Resources and supporting processes must be supplied by ecosystems beyond any formal urban borders (Luck, Jenrette, Wu, & Grimm, 2001). Nevertheless, acknowledging the three pillars of sustainability mentioned above, urban systems can become *more* sustainable than they currently are. In other words, sustainability is an ongoing process rather than an endpoint. Pursuing sustainability goals would require cities to better attend to human well-being, more effectively to encourage and to benefit from ecological processes and integrity, and better to promote social equity. Urban sustainability is thus a relative concept that requires understanding trajectories of change and the contributions those changes can make to joint and positive ecological, social, and economic processes in urban areas. Natural ecosystems are self-organized systems with long histories of adaptive capacity developed by evolution, selection, and migration, and they provide substantial lessons for sustainability science.

If sustainability is a socially negotiated set of goals for a human ecosystem or jurisdiction, resilience is the underlying mechanism by which sustainability might operate (Wu & Wu, 2012). Resilience refers to the capacity of a social–ecological system to adjust to internal and external shocks, yet retain fundamental features of its structure and processes (Ernstson et al., 2010; Holling, 1994; Pickett et al., 2012). In this ecological or evolutionary sense, resilience is different than that defined by engineers who are concerned with the capacity of a system to return to a pre-stressed state (Peterson, Allen, & Holling, 1998). The first, more ecological definition of resilience, acknowledges that systems likely do not have a fixed equilibrium point. Rather, it suggests that the ability to evolve,

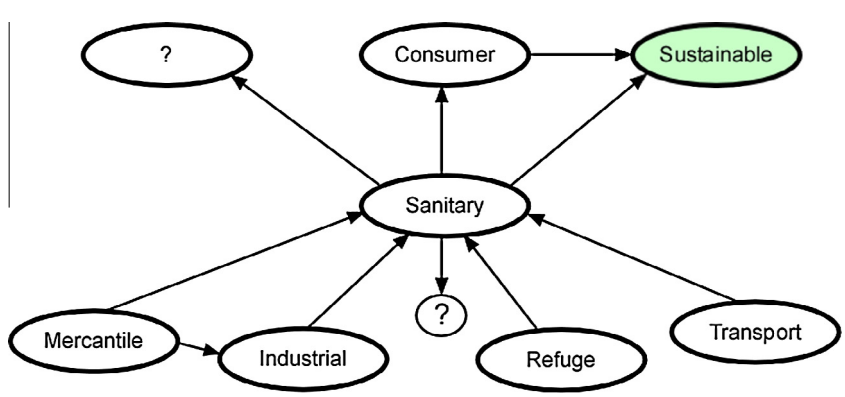

Fig. 3. Some possible transitions from the sanitary city to other city modes. The variety of possible transitions suggests that the transition from sanitary to sustainable city must be actively managed. Retrograde and undesirable transitions are possible as well, and must be guarded against. Note that, for the sake of simplicity, not all possible pathways toward the sustainable city are shown. Copyright of the Baltimore Ecosystem Study LTER. Used by permission.

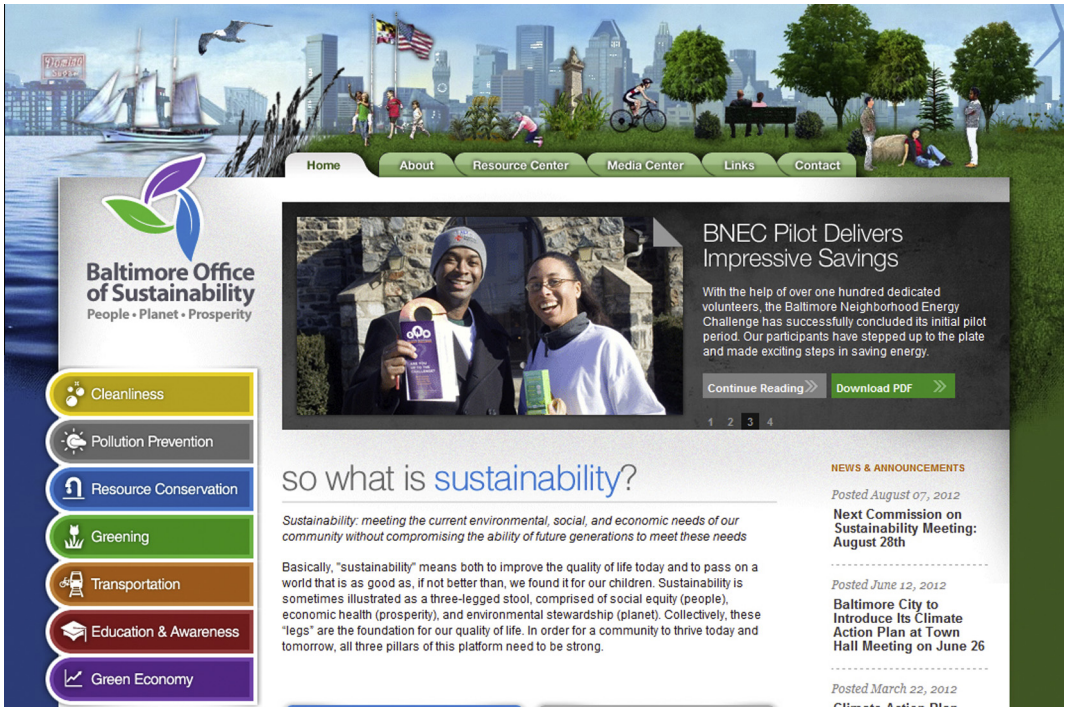

Fig. 4. An example of a municipal sustainability plan. The Baltimore City Office of Sustainability home page, indicating on the left the seven major components covered by the plan. http://www.baltimoresustainability.org/ accessed 1 September 2012.

adapt to, and learn from the changing relationships between system and environment are most relevant to systems based on living organisms and social interactions. Feedbacks, learning, genetic adaptations, natural selection, and cultural adjustment then become the most important features of systems (Table 1). Cities can incorporate, by design and by policy, more of the adaptive structures and processes that resilience theory suggests (Walker, Holling, Carpenter, & Kinzig, 2004; Yohe & Tol, 2002). In other words, they can amass the ecological, social, and built capital that can effectively prepare them for the shocks that are sure to come as a result of economic cycles and perturbations, climate change, environmental hazard, human migration, and changes in institutional and group activities, among many others (Vale & Campanella, 2005).

In biological systems, resilience appears as a cycle that begins with succession shifting from rapid growth to increasing structural investment, or ecosystem development shifting to increasing investment in maintenance. The cycle may be punctuated by periodic disturbance to the highly structured system, opening yet another bout of succession. For example, in extensive forested regions, there are complex mosaics of forest ages and architectures, which cycle through gaps, canopy closure, canopy disruption, and reorganization based on new invasion or sorting between juvenile plants that survive the disturbance events (Pickett, Meiners, & Cadenasso, 2011).

Panarchy theory extends this thinking to suggest an adaptive cycle that explains how systems are able to adjust and adapt to disturbance or stress events (Gunderson & Holling, 2002; Pelling & Manuel-Navarrete, 2011; Scheffer, Westley, Brock, & Holmgren, 2002; Walker et al., 2004). Pelling and Manuel-Navarrete (2011) present a version of the adaptive cycle particularly useful for urban ecosystems (Fig. 5). Hence, it is relevant to the transition of urban areas, and may be helpful to understanding the potential of cities to become more sustainable through resilience (Folke et al., 2012; Gunderson & Holling, 2002; Scheffer et al., 2002). The adaptive cycle suggests that during early phases of urban settlement, there is little established structure and infrastructure. Hence, there is vast opportunity for utilizing uncommitted resources. Furthermore, initial settlements may have relatively little regulatory or civic structure, encouraging rapid deployment of investment and opportunistic filling of space. As urban settlements grow, just as in natural ecosystems, they tend to become more structurally complex, exhibiting "insurance" through greater compartmentalization of redundant processes, and greater investment in maintenance. When complex systems develop large investments in physical structure or over-connected information flows, may be especially sensitive to disruption by external events. This is because it is difficult to quickly reallocate such invested physical structure or to transfer information in ways that might respond to the disturbance event. Severely disturbed complex systems may reorganize to simpler systems capable of rapid allocation of resources and rapid growth once the disturbance has passed. If other severe disturbances do not occur soon after the event that reorganizes the system, the system can undergo further growth and development in complexity.

In urban systems, the cycle may reflect sensitivity to economic or physical catastrophe, followed by neighborhood or district revitalization and recovery of livelihood and human well-being (Vale & Campanella, 2005). The adaptive cycle may also help explain how urban systems become "locked in" to certain courses of action in the face of novelty that would in fact be better served by innovative approaches (Pelling & Manuel-Navarrete, 2011). At the same time, physical investment and regulatory programs become set, and then act as inertia or potential brakes on change and adaptation to novel conditions. Such fixed costs and set ways of action may make the system susceptible to extraordinary events that have not been accounted for in the existing structure or norms for action. Such rigidity and inertia may prevent an urban system from best responding to unexpected change or perturbations.

The sustainable city has several key characteristics motivated by human values. These are discussed in the literature under a variety of rubrics: the humane metropolis (Pickett, Buckley,

Table 1
Adaptive processes in social and biophysical realms.

1. Social adaptive processes
   a. Technology development and acquisition
   b. Decision-making
   c. Locational choice
   d. Risk spreading
   e. Generating, managing and vetting information
   f. Change in public perception and valuation
   g. Institutional change
2. Social conditions favorable for adaptation
   a. Range of technologies available
   b. Available resources
   c. Demographics
   d. Human capital
   e. Social capital
      i. Ability to deal with information
      ii. Information networks that work
   h. Institutional change capacity
3. Biophysical adaptive processes
   a. Selection and Evolution
   b. Meta community dynamics and change
   c. Successional capacity
   d. Organism-level plasticity, acclimation, etc.
   e. Regulatory feedbacks on populations
   f. Ecosystem nutrient retention
4. Biophysical conditions favorable for adaptation
   a. Species and functional group richness and availability
   b. Abundant resources
   c. Intact, "healthy" key structures
   d. Scaled connectivity
   e. Compartmentalization of disturbance

Kaushal, & Williams, 2011; Platt, 2006), green urbanism (Beatley, 2000), integral urbanism (Ellin, 2012), sustainable urbanism (Williams, 2007), and ecological urbanism (Mostafavi & Doherty, 2010; Spirn, 2012). We exemplify the features that should characterize sustainable cities through the lens of the humane metropolis. Humane metropolises are described as those that (1) protect and restore ecological services in cities and suburbs, (2) promote physical and mental health and safety of residents, (3) enhance efficiency by conserving energy, matter, water, and time, (4) facilitate social and environmental equity by being inclusive, and (5) maintain a sense of community and a sense of place (Platt, 2006). In addition to the general features of sustainability, social scientists point to the great significance of governance as a tool for or constraint on sustainability, depending on circumstances. For example, Pincetl (2010) has proposed the institutional arrangements – both within and outside of formal government – that may be necessary to promote sustainability. Social scientists have also documented the processes that lead to environmental injustices (Boone, 2002; Bullard, 2005; Cutter, 2006). Another group of urban scholars and professionals — urban designers — has suggested a large number of strategies and best management practices that can produce more "ecological work" in urban areas, mitigate environmental hazards and vulnerabilities, and stimulate a sense of delight in urban residents (McGrath, 2011).

Ecological processes in cities: a foundation for sustainability

The sustainable city will also include effective ecological processes. Recent reviews detail the rich variety of ecosystem services and ecological wealth that often exists in cities (Brown & Grant, 2005; Pickett, Cadenasso et al., 2011; Pincetl, 2010, 2012). We will highlight a few examples here.

Urban areas are generally warmer than the surrounding agricultural or wild lands. This well known phenomenon is called the urban heat island (Oke, 1982). Heat islands are caused by the reduced transpiration by vegetation in most cities, the generation of waste heat, and by the exposure of highly absorptive built surfaces to large solar radiation loads. Such surfaces subsequently reradiate thermal energy, increasing air temperatures. The contrast is typically greater at night. An exception to the generalization of the excess of urban heat is certain aridland cities in which irrigated vegetation transpires freely and cools the immediate microclimate, as does evaporation from open water surfaces. Thus, Phoenix, AZ, is actually cooler at some times of day than the surrounding native

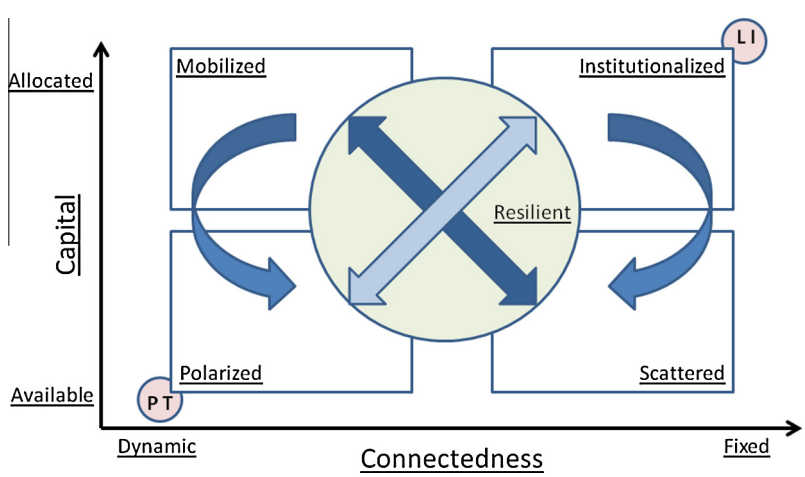

Fig. 5. An adaptive cycle model of social–ecological resilience. Two dimensions define a conceptual space in which resilience dynamics can be charted: the amount of capital or wealth; and the degree of connectedness. When a system has low wealth or capital, it may be organized to exploit available resources. Exploitation allows the system to reorganize. Once high capital is attained, internal allocation of resources favors maintenance or conservation within the system. High connectedness is also associated with the capacity of a system for maintenance. However, high capital and high connectedness make a system vulnerable to shocks and disturbances, and when an extreme enough event occurs to disrupt the structure or the metabolism of conservation and connection, collapse ensues. Such collapse, if it is not associated with destruction of the basic resources upon which wealth is built, and based on the availability of entities – be they organisms or institutions – that can exploit the resources freed by disturbance, then exploitation and reorganization can begin anew. While the adaptive cycle is usually shown as a Moebius strip in the conceptual space, this version highlights resilience as a capacity to respond in four different ways depending on the environmental conditions and operation of disturbance events. Resilience is shown in the center of the model, indicating that the capacity to respond to shocks and disturbances is flexible relative to capital and connectedness. Events extreme enough to reduce resource availability, including limited social adaptive capacity, may send a system into a "poverty trap" (PT) from which it is difficult if not impossible to emerge. Similarly, highly conservative and connected systems may create a trap of rigidity or "lock in" (LI). The version redrawn here is based primarily on Pelling and Manuel-Navarrete (2011) and using ecological concepts as axis descriptors, and additional insights from various sources (Biggs, Westley, & Carpenter, 2010; Holling & Gunderson, 2002; Scheffer et al., 2002).

desert while it fails to cool down at night compared with the desert (Brazel, Selover, Voce, & Heisler, 2000). Increasing urban tree canopy in general, and strategic plantings around buildings is well known to moderate heat extremes for residents and reduce energy use for cooling (Nowak, Wang, & Endreny, 2007). In many cities, residents of poorer or otherwise disadvantaged neighborhoods enjoy less urban tree canopy, are exposed to greater extremes of heat, and are consequently at greater risk of morbidity and mortality (Huang, Zhou, & Cadenasso, 2011). Mitigation of the urban heat island can exploit increased vegetation cover and improvements in the local water cycle.

A second example of ecological processes in cities is the flux of nitrate in waters draining urban areas (Groffman, Law, Belt, Band, & Fisher, 2004). A principle of ecosystem ecology is that limiting nutrients will be conserved or transformed within ecosystems, rather than released into downstream or downwind flows. This generalization is relevant to the behavior of nitrate (NO_3^-) that in high amounts is a groundwater pollutant that can impair human health, and that in coastal waters leads to overproduction of aquatic algae that deplete the oxygen required by other organisms. Dead zones can result. Estimates of the nitrogen budget in Baltimore, MD, have documented that the green components of the metropolitan area show this ecosystem function to some degree. As expected, the forested watersheds in the urban mosaic are most retentive, keeping more than 90% of the nitrogen estimated to be deposited on them via the atmosphere. Notably, catchments in the metropolis that possess high proportions of residential parcels with lawns retained as much as 74% of the nitrogen input. This is a significant ecological process within the urban matrix. The structure of the riparian zone and its degree of connection to ground and surface water flows is an important controller of the process (Groffman et al., 2003). Hence, promoting biological retention processes in streams and waterways can contribute to sustainability.

Another important ecological process in urban systems is natural disturbance. In ecology, a disturbance is defined as an event that disrupts the three dimensional structure of a system, and which may as a consequence affect the metabolism, composition, and subsequent dynamics of the system. Many natural events that are capable of such disruption occur relatively infrequently, and their exact timing and intensity are not precisely predictable in advance. Earthquakes, wildfires, flooding, high winds, and snow and ice loading are among the environmental hazards that urban areas must plan for. Disturbances are conceived as pulse events. Other events that have longer duration can also be important disruptions in urban systems, and may stress flows and interactions prior to triggering any changes in the physical structure. Droughts, heat waves, sea level rise, and climate change are examples of such more persistent, or press-type hazards facing urban socio-ecological systems. In many cases, these hazards disproportionately impact economically and socially vulnerable populations, revealing urban structural inequalities, as demonstrated by Hurricane Katrina in 2005. Planning for resistance where appropriate, and preparing adaptive, ecological responses where the events are likely to be so large as to overcome hardened engineering solutions, are required.

Urban ecosystems are clearly social–ecological systems. Most conceptualizations of such systems are inherently interdisciplinary (Collins et al., 2011), but still tend to separate the structure and function of social and ecological components. Childers et al. (2013) present a more integrated conceptualization of cities as social–ecological systems, where the structural component includes both built and designed elements and natural features and where the functional component includes the interactions of human decisions and ecological processes. The urban phosphorus (P) budget for Phoenix AZ USA (Metson, Childers, & Aggarwhal, 2012; Metson et al., 2012) is an example of this more transdisciplinary conceptual approach. This budget found remarkably tight urban cycling and retention of P that was largely regulated by decisions tied to water conservation, particularly in the urban agricultural sector. This serendipitous coupling of P and water cycling in the city was revealed by considering human and biophysical components of the urban ecosystem as integrated, not separate.

These examples are only indicative of the kinds of ecosystem processes, some of which may be recognized as ecosystem services by policymakers or citizens, that exist in cities. The connection of services with urban metabolism are important human outcomes in cities (Pincetl, 2012). Taking these processes into account and, indeed, enhancing them and making more space in urban areas for the amenities they represent, is an important tool for sustainability (Beatley, 2000; Christensen, MacDonald, & Denning, 2011; Farr, 2008; Sassen & Dotan, 2011).

Urban transformations toward sustainability

The strategies chosen to advance sustainability will depend upon the starting point. Each of the many city modes can act as a starting point (Fig. 3). A city of consumption, sheltering economically motivated migrants, might require a different pathway toward sustainability than a city of refuge, for example: A city of refuge might urgently require the basic infrastructure taken for granted in post-industrial sanitary cities.

While any transformation among city modes could be addressed ecologically and strategically, we focus on the sanitary-to-sustainable city transformation for two reasons. First, there is widespread concern with developing sustainable cities worldwide (Sustainable Cities Institute, 2012; Williams, 2007), and second, the sanitary city is a common starting point in the Global North and a traditional goal in the Global South (Fig. 3). Furthermore, sanitary cities in the Global North and increasingly elsewhere, are currently often cities of commercial consumption, which have a disproportionate impact on global unsustainability. These cities reflect the political and economic program of modernism as it emerged in the late 19th and early 20th centuries.

We have focused on the transition from the sanitary to the sustainable city to illustrate the potential improvements that can be achieved by an ecologically informed urban transformation. However, the other city modes all have shortcomings that can be overcome by the sustainable city as well. Each of these other city modes focuses on a specific problem or aspect of well-being – refuge, consumption, manufacturing, etc.

Features of the sanitary city

There are eight key features of sanitary cities. Details are summarized by Melosi (2000), Grove (2009) and Pincetl (2010, 2012).

1. *Solutions to problems of pollution and provision of services are mainly engineered*: For example, in the sanitary city, drinking water purity is usually ensured by filtration plants and the addition of chlorine, and stormwater is transported from city streets and prevented from causing flooding via storm drains and channelized streams. Notably, several of these engineering strategies, such as wastewater treatment or drinking water filtration, exploit and concentrate natural processes, and the piped infrastructure often still follows topography.
2. *Hazards are segregated from residential areas if possible*: Zoning that separates industrial and commercial functions from residential blocks is an example of functional segregation. In the industrial city, with its early reliance on walking and horse-powered commutation, and later emphasis on public transportation, living close to work in the factories and ports was considered a benefit. The sanitary city, however, is characterized by discrete residen-

tial, commercial, and industrial zones. Indeed, these distinctions are so pervasive as to be encoded in the traditional and common urban land use classifications (Anderson, Hardy, Roach, & Witmer, 1976). Notably, the segregation of hazards has often been inequitable, with the risk disproportionately borne by communities of color, or by the economically disadvantaged, or by communities who are otherwise disempowered in the process of environmentally relevant decision-making.

3. *Wastes are removed*: The concentration of people and industrial processing of food led to a concentration of refuse, offal, and contaminated water and material. The sanitary city solution was to reduce solid wastes in incinerators or remove it or its residue to landfills; fouled water was transported away from urban centers via sewers. Such waste removal values the speed of flow over local processing, which is contrary to the way more natural ecosystems function.
4. *Management functions reside in separate municipal departments*: For example, the metropolitan government of Louisville, KY, which may be considered a typical, mid-sized American urban area, lists 25 departments on its home page. The metropolitan government encompasses the city of Louisville and Jefferson County. A full listing of departments and programs totals 48 (http://www.louisvilleky.gov/DepartmentList.htm; accessed 1 September 2012), although to be fair, several reflect sustainability initiatives and concerns that emerged relatively recently. Typical sanitary city departments include those that deal with air pollution, deaths, emergency management, economic development, justice, corrections, parking, health, human resources, fire, water, parks, police, planning, revenue, and solid waste. The separation of functions into discrete departments and programs can contribute to the institutional inertia that often stymies resilience (Childers et al., 2013).
5. *Management is conducted by specially trained experts*: The growth of the sanitary city and the professionalization of expertise in America went hand in hand. Indeed, one of the successes of the sanitary city is the congruence of its structure with that of professional training in such fields as engineering and urban planning. Trained professionals staff city and county departments, and professional certification is required for employment in many cases.
6. *Public resources support the development and maintenance of infrastructure*: Although civic organizations are important in the empowerment and functioning of the sanitary city (Buckley, 2010), the primary responsibility for infrastructural development and maintenance in the sanitary city is in the hands of municipal government, and is paid for with tax-supported public funds (Pincetl, 2010).
7. *Formal government is the predominant actor*: Management and planning decisions are hierarchically promulgated from the top, and are guided by regulations such as zoning and building codes. Even when activity takes place in the private realm, public good is expressed in constraints on the form of construction and the use of structures and lands.
8. *The demographic transition is considered to be a universal pattern associated withurbanization*. The many personal and social benefits accruing to the demographic transition are seen to parallel sanitary urbanization. The sequence of development, akin to a life cycle for society, seems to tacitly embrace this assumption. The terms "developed" and "developing," or Global North and Global South, place nations and cities on this ladder of assumed progress.

Features of the sustainable city

The ideal of the sustainable city contrasts with all of these aspects of the sanitary city noted above. Although the successes of the sanitary city should not be dismissed, in order to promote sustainability, it will be necessary to go beyond them. Indeed, some components of the sanitary city will have to be reinvented and replaced with institutions and infrastructures that can better facilitate sustainability resilience (Childers et al., 2013; Ernstson et al., 2010; Pincetl, 2012). Each of the eight features described above represents an important point of contrast between the sanitary city and the sustainable city (Grove, 2009; Pincetl, 2010):

1. The sustainable city will include ecological as well as engineered infrastructure to provide ecosystem services, such as stormwater control or climate mitigation. On-site management practices will be favored over those that simply displace hazards, in many cases leading to a decentralization of infrastructure. With this comes recognition that environmental interventions should have multiple purposes and benefits. For instance, constructed urban wetlands can provide several benefits, including recreational opportunities and wildlife habitat in addition to improved water quality.
2. Hazards will be addressed in all land cover types, and an attempt will be made to reduce vulnerabilities throughout the urban system. Moreover, sustainability recognizes that vulnerable people should not be disproportionately exposed to these hazards. Rather than segregating nuisances and polluting sites, efforts will be made to reduce, prevent, or mitigate hazards across the entire city region. The strategy of hazard segregation is often enshrined in regulations, and can consequently be a barrier to, or inertia against, productive mixed-use solutions that create or restore lively urban neighborhoods (Ben-Joseph, 2005). This kind of segregation of use will be disfavored in the sustainable city.
3. Wastes will be reduced in volume, and emphasis will be placed on recycling or reuse of any wastes that are generated. This applies to household and institutional waste streams, and to demolition materials.
4. Management and planning will be integrated, and municipal departments will overcome or do away with boundaries. Common problems that cross modes of transport and infrastructural networks will be identified and addressed jointly.
5. Management will be conducted not only by experts with specialized training, but with the involvement of communities, neighborhoods, and private organizations. Governance in the sustainable city will be flexible and decentralized, and therefore more adaptive to community initiatives for sustainability. For example, the diverse ways cities institutionalize urban garden initiatives offer insights into governance models for sustainability (Barthel, Folke, & Colding, 2012; Rosol, 2012).
6. Public resources will not be the only ones spent for management and infrastructure in the sustainable city. Public resources will be complemented by resources from the private sector or by substitution of management undertaken in the private and commercial sectors.
7. Public–private partnerships will be necessitated by the fact (Item 6) that resources will no longer depend exclusively or primarily upon the public purse. Public–private partnerships will be a part of the management strategy in the sustainable city and decision-making will extend beyond formal government structures to involve all stakeholders. Both public and private land holdings will likely be involved in promoting urban sustainability.
8. The demographic transition, in which sanitary urbanization is associated with reduced fertility and mortality rates and their associated social benefits, is recognized as a special case that operates only under certain historical circumstances. Hence,

the demographic transition alone will not answer the problems of urbanization in many places. Active involvement in improving quality of life and livelihood, a tenet of stewardship (Chapin et al., 2009), will be required to ensure the well-being of urban dwellers and ecosystem services in and around sustainable cities.

The eight features of the sustainable city can be summarized by a set of overarching themes: (1) Employ more bottom-up management and decision-making; (2) Develop more holistic approaches to top-down decision-making; (3) Favor solutions that rely on decentralized infrastructures; (4) Generate incentives to replace aging sanitary city institutions and infrastructures using the first three of the eight points above, rather than simply repairing the sanitary-era institutions and norms (for more see Childers et al., 2013).

The sustainable city is a vision, tuned to the realities of each place and culture, that attempts to overcome the shortcomings of other city modes. Urban sustainability is the process by which cities transition towards these visions (Childers et al., 2013; Grove, 2009; Pickett, Cadenasso et al., 2011; Pincetl, 2010). Furthermore, the sustainable city also includes the important normative aspects of city functions associated with people's values and desires. It is, in other words, something more than the traditional or specialized city modes.

The metacity: a dynamic framework for urban transformations

We use the metacity concept in a new way to help understand and promote transformations to the sustainable city. In 2007, the United Nations introduced the term "metacity" to indicate a city that (1) has more than 20 million residents, (2) is larger than a megalopolis, (3) is polycentric, and (4) has diffuse governance. It is the pinnacle of a hierarchy of hugeness that starts with mere cities, and extends by increasing size, extent, and spatial complexity, to the metropolis, through the megalopolis, and ultimately to the hypercity or metacity. The ultimate terms on this ladder seem to be mainly structural, however, as defined by the UN (McGrath & Pickett, 2011). Yet, there is much to be gained from thinking about the new modes of cities functionally, rather than as merely a reflection of population size. The term *metacity* can serve this purpose.

The metacity links with key conceptions in ecology. Ecologists are familiar with process-oriented uses of the prefix, meta. Metapopulations and metacommunities both involve spatially dispersed units, each of which may be established, change, or disappear based on its own internal dynamics, relationships with the local environment, and migration from other units (Hanski & Gilpin, 1997; Leibold et al., 2004). For example, a colonizing plant that requires abundant light and mineral nutrients may thrive only in canopy gaps created by disturbance in forests. As gaps close with the spread of intact, neighboring canopies, or with the rise of tree seedlings and saplings into the gap, the colonizing plants in that spot typically succumb to competition from longer-lived, shade tolerant species. At the same time, seeds of the colonizing species may have dispersed to other, younger gaps or may have entered dormancy in the soil beneath the closing forest canopy. Those dispersed or stored propagules can give rise to new active, reproducing populations of the colonizing species after subsequent disturbances. The species is then said to behave as a metapopulation, or a population comprising smaller, spatially distributed subpopulations. Metapopulations thus consist of distinct subpopulations that interact via migration, gene flow, and persistence.

A collection of species, that is, a community, can also be isolated in space from other instances of that community, and each isolate or potentially suitable spot is differentially affected by a number of environmental processes. These differentials include exposure to physical disturbances, persistence, succession, dispersal of constituent species, and colonization of new species. These differentials generate a shifting mosaic of communities (Leibold et al., 2004). This, too, is labeled using the prefix "meta." A metacommunity is a dynamic set of patches of a community type differentially distributed and partially isolated in space. We argue that the functional and spatial prefix, meta, can apply in urban theory as well as in biological ecology in a way that considerably expands on the UN's population-based definition (McGrath & Pickett, 2011).

In the metacity, the spatial units or patches might appear as neighborhoods, zones, and districts (Plunz, 2007; Shane, 2007). Each neighborhood would have its own character and social value, such as commercial, industrial, or residential, or would represent some mixture, such as street level commerce and upper story residence. More specific activities and outcomes could be identified as well. A particular study or policy intervention might focus on patches representing certain kinds of innovation, or those sheltering sub-cultures, or producing very specialized products (Shane, 2005). The patches would furthermore be characterized by the specific land cover elements they comprise, including vegetation type, amount, and layering, the presence and condition of paved and bare surfaces, or built structure configuration, height, and density (Cadenasso, Pickett, & Schwarz, 2007).

Patches in the metacity can change due to vegetation succession, planting, and management of ornamental species; establishment and maturation of families; migration of different social groups; the ebb and flow of economic investment; aging of building stocks and infrastructure; spatially focused policy decisions, and many others. The patches are differentially connected by networks such as transportation infrastructure, water mains, sanitary sewers and storm drains, communication, commuters, and by the fluxes of water and air. The dynamism and interaction of such patches is emphasized by the term metacity (Fig. 6).

In defining the metacity, the UN did note that they had multiple centers, and due to spatial extent, that governance was likely to be spread over many jurisdictions. Governance is further complicated by the devolution of many functions from formal government to

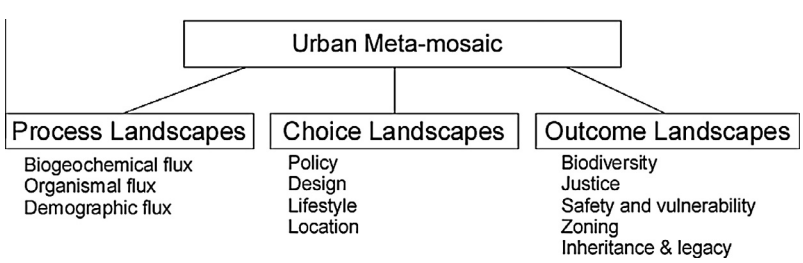

Fig. 6. The metacity as a framework for urban metamosaics. The spatial mosaics of city–suburban–exurban systems reflect (1) the fundamental social and ecological processes, (2) the choices made by individuals and various formal and informal institutions, and (3) the resultant environmental and social outcomes that exist at any given time. A dynamic view emerges when the feedbacks between outcomes, processes, and choices are considered over time. For simplicity, those feedbacks are not represented graphically in the diagram, but are conceptually key to the model. Copyright Baltimore Ecosystem Study LTER. Used by permission.

non-governmental organizations, community groups, and private enterprise.

As cities transform, the functional metacity concept – regardless of size – may provide a tool for advancing the sustainable city. There are several advantages of the metacity concept for sustainability. First, the metacity clearly acknowledges that urban areas are mutable. Citizens, scholars, and policymakers who wish to enhance sustainability can take advantage of the places where change is occurring, or where it is most likely in the future. Second, the patchy nature of the metacity at many spatial scales suggests that those who plan and manage urban areas can identify those patches where ecological processes can best be integrated into the urban fabric. Indeed, identifying even marginal gains in the ecological contribution of any kind of patch will promote sustainability. The metacity concept suggests an adaptive policy and management approach based on heterogeneity of both biophysical and social mosaics, and not on traditional political boundaries. Third, the connections between the different spatial units in the metacity, either as a result of adjacency, infrastructural networks, or long distance connections, suggest that services and amenities can be shared across the larger mosaic. Fourth, the metacity concept is expressly hybrid in its intent: biophysical and social patterns and processes are intended to be represented in its shifting mosaics. Finally, the spatial heterogeneity and dynamism of metacities focuses attention on local amenities and ecological processes, as well as on connecting these with regional fluxes that affect ecosystem services. In an era of crisis and transformative opportunity, it presents the opportunity for designing anew or restoring patches to enhance the contribution of biological ecosystem processes to urban life.

Conclusions

Social theorists use the term metatheory to indicate an analytic approach that seeks to understand the shared and divergent assumptions of social explanation (Ritzer, 2001). In some ways, metacities are a form of metatheory, in that they offer us rare insights into the dynamic processes of urban transformation and help us think about the diverse opportunities for sustainability. The fact that so many cities are now being built or are poised for revitalization means that there is the opportunity to urbanize in different ways than we have in the past. Compared to existing cities, better integration of ecological processes may be most successful in "new" cities. Greater attention to environmental equity among citizens is also possible in new cities. But such benefits can accrue to existing cities as well. As older city cores become less dense, there is an opportunity to reinvigorate ecological processes within their neighborhoods in ways that benefit citizens as well as the environment. Older cities also have great stores of aging infrastructure that will have to be replaced in the coming decades. Thus, all cities, whether old or new, can be made to be *more* sustainable.

The traditional theories about transitions – the demographic transition, which is one facet of the life cycle of industrial development, or the transition from industrial to sanitary cities – may not be good models for all cities, whether they are just emerging or old and crying out for repair. Rather, the social ideal of the sustainable city as a transitional process, and the spatially complex and dynamic model of the metacity may suggest a new turn toward social–ecological stewardship in the world's cities. Sustainability is not an existential exercise that waits for a transition to occur – it is a transition we can choose that demands intervention to design and build the future we want.

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