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Theoretical Perspectives of the Baltimore Ecosystem Study: Conceptual Evolution in a Social–Ecological Research Project

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The Earth's population will become more than 80% urban during this century. This threshold is often regarded as sufficient justification for pursuing urban ecology. However, pursuit has primarily focused on building empirical richness, and urban ecology theory is rarely discussed. The Baltimore Ecosystem Study (BES) has been grounded in theory since its inception and its two decades of data collection have stimulated progress toward comprehensive urban theory. Emerging urban ecology theory integrates biology, physical sciences, social sciences, and urban design, probes interdisciplinary frontiers while being founded on textbook disciplinary theories, and accommodates surprising empirical results. Theoretical growth in urban ecology has relied on refined frameworks, increased disciplinary scope, and longevity of interdisciplinary interactions. We describe the theories used by BES initially, and trace ongoing theoretical development that increasingly reflects the hybrid biological–physical–social nature of the Baltimore ecosystem. The specific mix of theories used in Baltimore likely will require modification when applied to other urban areas, but the developmental process, and the key results, will continue to benefit other urban social–ecological research projects.

Keywords: framework, social–ecological system, theory development, urban ecology, urban ecosystem

Urban ecology is often introduced as a practical concern, driven by the exponential growth of the world's urban population, the spread of urbanized lands in both developed and developing countries (Seto et al. 2017), and the intersection of urbanization and climate change (Childers et al. 2015). These urgent concerns may lead researchers to neglect theoretical justifications for the science. Such neglect may also characterize a young, interdisciplinary field. But there are existing theories, concepts, frameworks, and models (box 1) that stimulate the growth of urban ecology.

The Baltimore Ecosystem Study (BES) has continually employed theories throughout its two decades of work. Therefore, exploring the evolving use of theory in BES should be useful for theoretical development elsewhere in the growing interdisciplinary field of urban ecology. Because there is no firm, general urban theory that incorporates the insights of contemporary ecology, the field must draw on many theoretical tools from other disciplines (McPhearson et al. 2016). The suite of tools and their degree of sophistication and connectedness will likely continue to grow in the future. Indeed, experience with mature theories, such as evolution or succession, suggests that detail, structure, and scope of theories change. Some of these changes may be large enough to qualify as changes in paradigm—a sort of metatheory in the background of any science (Devlin and Bokulich 2015). Evolution of theory is healthy and expected.

Theories are broad conceptual devices aimed at explanation and understanding of processes and structures in the world (Scheiner and Willig 2011, Laplane et al. 2019). They consist of statements of their domain, assumptions, generalizations or laws, models, hypotheses, and frameworks (Pickett et al. 2007). They are often characterized by methodological or empirical approaches, and connect with practical concerns on various scales. In this article, we explore the development of urban theory through the experience of

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Box 1. Theory components, contrasts, and relationships.

What theory is and how it is used is a broad and complicated topic. Although a detailed description is beyond the scope of this article, the nature and use of three key terms help explain theory evolution. Further details can be found in Pickett and colleagues (2007).

Theory is an overarching, general conceptual tool that generates expectations and explanations within a broad domain. As such, it is an explicitly linked system of conceptual, empirical, and speculative components. Roughly a dozen specific components can be parts of a complete theory, but we focus on three that are not primarily empirical ones to clearly represent theory evolution.

Concepts are regularities in events or objects designated by a label. They may sometimes be abstract, whereas, in other instances, they can identify a focused body of fact. For example, the watershed concept is an abstraction that encompasses the myriad actual watersheds encountered in the world.

Models represent the structure, relationships, and change in specific foci within a theory. Models are conceptual representations specifying the components of a system of interest, their interactions, the nature of their dynamics, and the physical, temporal, or mechanistic limits of the processes involved. For example, a specific ecosystem model represents the actual links and flows that occur within an designated place.

Frameworks provide the conceptual structure for a theory. They show how the logic, mechanisms, or processes connect to each other. Frameworks often indicate how the various complementary or alternative models a theory employs are related. For example, a framework for patch dynamics theory organizes the driving processes into patch differentiation, boundary configuration and function, and mosaic-wide processes and change.

A single one of these components—concept, model, or framework—may sometimes be used as a metaphor or shorthand label for the entire theory.

BES as a long-term research project designed to understand metropolitan Baltimore, Maryland, as a social–ecological system. We begin by describing the two main theories that initially anchored the interdisciplinary project. Then we present the three major theories that were used to bridge between the starting theories during the first decade of BES (1997–2007). We show how empirical surprises and the limitations of the five more focused theories we applied during the first decade led to theoretical refinement or novelty. The shortcomings of these theories for understanding integrated social–ecological systems, or for practical application of our growing roster of long-term results led to additional theoretical advances in the second decade of BES (2007–2017). We use ten cases to show how this additional theoretical growth occurred. One of the theoretical advances is a practical conception of complexity, which we use to indicate how the remaining cases are linked. Our complexity theory illustrates key links between social and biophysical processes in our urban system. Finally, we point to emerging frontiers and future needs for urban theory (figure 1).

Theory and the establishment of the Baltimore Ecosystem Study

This section describes the initial theories that were used to motivate and structure the earliest years of BES. The project was established as a long-term ecological research (LTER) site by the National Science Foundation in 1997. A formative goal for BES was cross-disciplinary integration between ecological and social sciences. The LTER program had, up to that point, emphasized five core ecological processes to help discover long-term changes in all biomes, but its roster of sites did not include ecosystems in which people were an integral component or driver of change. Integration of social–ecological processes was identified by the request for proposals for urban LTER sites (table 1). The linking of ecological and social structures and processes had been explored only fitfully in North America (Kingsland 2005, 2019). However, social–ecological systems thinking had successful precedents in Europe (for a discussion, see, e.g., Folke et al. 2016, Lachmund 2013, Liu et al. 2007), which stimulated our thinking.

Theory is required for successful integration (Pickett et al. 2007). But in 1997 there was no single theory available for social–ecological integration encompassing entire urban areas in a way that included the perspectives and insights of ecology (Collins et al. 2011). Furthermore, integrations would have to be founded on established or textbook theory. If integration is likened to bridge building, the integrative bridge spans, however speculative and novel, must be firmly anchored on the piers of accepted theory (Cadenasso and Pickett 2008).

Two theories were adopted to establish BES and to initiate social–ecological integration: stress and disturbance gradients (Pickett and White 1985, Fox et al. 2011, Grime 1979) and the watershed (Likens 1985, 2001, Vannote et al. 1980, Fisher 1992, 1997).

Gradient theory had been well exercised in ecology (Whittaker 1967). By the 1970s both stress gradients and disturbance gradients were firm enough that they could be combined into a theoretical structure explaining the evolution of organismal strategies that underlay community organization (Grime 1979). Similarly, these two processes

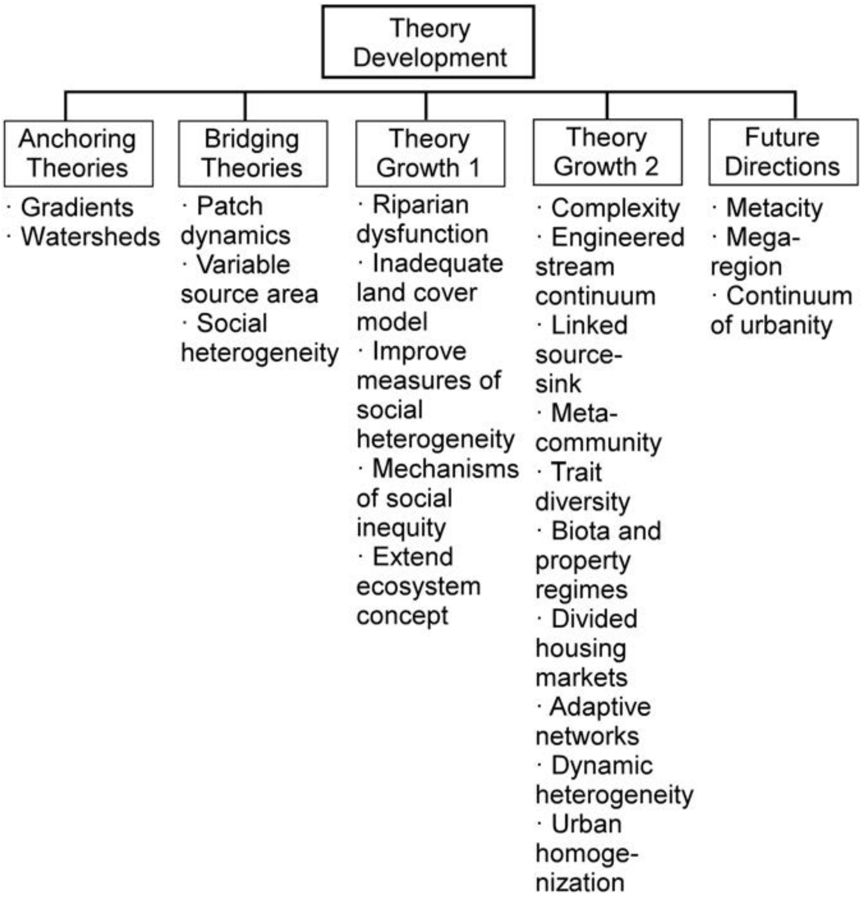

Figure 1. Phases of BES theory development and implications for some future urban theories. The first anchors and first bridges were established at the outset of BES. Growth in the next two decades resulted from empirical surprises, emergence of long-term trends, and conceptual refinements to ecological theory or integration between social and biophysical processes that were required for an urban focus. Aspects of the theories used and refined in BES suggest needs and opportunities for future urban theories.

had been combined in a theory of plant community succession as the sorting of species presence or dominance along shifting gradients of stress over time since a disturbance (Meiners et al. 2015). These gradients are embedded in the workings of adaptive resilience as well (cf. Holling 1973, Gunderson and Holling 2002).

Application of complex gradient theory to cities was pioneered in metropolitan New York by McDonnell and colleagues (1997, Pouyat et al. 2008). They sought to explain differences in ecosystem processes in patches of closed canopy mixed-oak forests on the same bedrock extending from the Bronx, NY through rural Northwestern Connecticut. Urbanization was assumed to generate gradients of stress and disturbance that could be assessed using this transect. This idea has been applied widely in urban ecology well beyond New York (Niemelä et al. 2002, Boone et al. 2012). Differences in forest structure, soils, mycorrhizal fungi, earthworms, reproduction of canopy trees, contribution of exotic plants, heavy metals, soil water repellency, litter dynamics, soil-to-atmosphere greenhouse gas fluxes, and nitrogen dynamics were among the profound differences discovered along the transect (Goldman et al. 1995, Medley et al. 1995, McDonnell et al. 1997, Groffman et al. 2006).

Gradients of stress and disturbance can also be discovered using a mosaic approach rather than sampled along a linear transect. BES examined sites scattered in a complex mosaic including old rowhouse neighborhoods, old commercial and industrial districts, late nineteenth and early twentieth century suburban developments, agricultural land, subdivisions dating from the early postwar era, new exurban residential subdivisions, commercial and light industrial nodes, and forested lands (Pickett et al. 2001, Grove et al. 2015). A founding goal of BES was to quantify the stresses, disturbances, and the ecosystem responses to them, using the array of sites as a measurement tool, and the gradient as an analytic tool. This mosaic of sites served as the raw material for *conceptual* gradient analyses that could be interpreted as continua of stress and disturbance (Qureshi et al. 2014). The theory of stress or disturbance gradients was combined with the theory of the watershed in the first attempt at theoretical integration in BES (Pickett et al. 2001).

The watershed as a theoretical and methodological tool had been used in nonurban LTER sites for a long time (Swank and Crossley 1988, Bormann and Likens 1969, Likens 2001). This theory is so familiar (e.g., Black 1991) that its conceptual depth and utility may not be obvious. Watershed theory assumes that areas or volumes of the Earth are tied together by overland and subsurface flow of water delivered to them. Conditioned by the topography and geomorphology of a watershed, water can act to transport or, through interaction with biological organisms and the structures they create on or near the surface, can act to transform, concentrate, or release materials, nutrients, and contaminants downstream. The integrative potential of watersheds explains their great theoretical utility (Bormann and Likens 1969, Fisher 1997).

Forested LTER sites, such as the H. J. Andrews in the temperate rain forest of Oregon, the Coweeta hydrology laboratory in the southern Appalachian mixed deciduous forest, or Hubbard Brook in the northern hardwoods forest, were powerful exemplars of the application of watershed theory. That Baltimore City and Baltimore County, the core jurisdictions of the Baltimore urban region, shared three

Table 1. The core research areas of urban long-term ecological research sites.

Core area	1980 LTER sites	1997 urban LTER sites
Primary production	X	X
Flow of inorganic matter	X	X
Flow of organic matter	X	X
Population studies	X	X
Disturbance	X	X
Human land cover change and ecosystem effects		X
Human–environment interactions		X
Integrate with K–12 education		X

Note: The first five listed are the core areas articulated at the initiation of NSF's LTER program in 1980. The remaining three were stated by NSF in 1997 as additional areas for proposals submitted in response to their call for urban LTER sites. Two of the new areas are research concerns, whereas the third is an engagement mandate.

distinct and obvious catchments—Gwynns Falls, Jones Falls, and Back River—made it easy to apply watershed theory. BES adopted the 17,150-hectare Gwynns Falls watershed as a primary research area because of the variety of landscapes it encompassed. This watershed ran from the suburbanizing fringe of Baltimore County through dense old residential and industrial districts adjacent to the mouth of the stream at the Inner Harbor on the Chesapeake Bay. Sample points were located along the length of the watershed in subcatchments and reaches representing different urban, suburban, agricultural, and exurban land use or land cover types. A complementary forested reference was established in the Pond Branch catchment in Baltimore County.

Watershed theory was valuable in Baltimore not only because of its synthesized hydrological and ecological functions, but also because its three watersheds had social significance. Several decades of watershed-based activism and education in Baltimore focused diverse social actors on the city's watersheds. Civic associations, city and county agencies, and the intergovernmental Chesapeake Bay Program all focused on and employed watersheds as part of their policy and management toolkits. The social and biophysical dimensions of the watersheds in Baltimore allowed BES to combine stress and disturbance gradient theory with watershed theory to motivate a pioneering research project in the urban ecosystem, so long neglected by ecological scientists in the United States (Kingsland 2019). Gradients of stress and disturbance and the watershed would be our first firm bridge piers.

The first bridging theories

The two theoretical bridge piers described above had been identified in the first BES proposal. In order to empirically integrate the biological, social, and physical components of the urban ecosystem, focus quickly shifted to three conceptual areas used to prioritize long-term data (Pickett et al. 2001). The theoretical bridge spans extending between gradient theory and watershed theory were hierarchical patch dynamics (Wu 2013, Wu and Loucks 1995), the variable source theory from hydrology (Black 1991), and sociospatial heterogeneity (Shevky and Bell 1955, Gottdiener and Hutchinson 2011).

First was hierarchical patch dynamics (Wu and Loucks 1995), which is an expansion of the basic concept of patch dynamics (Pickett and White 1985). The theory assumes that at various nested spatial scales (e.g., figure 2), patches, or more generally spatial fields, can be identified on the basis of differences in content, three-dimensional structure, and spatial configuration. Furthermore, the theory asserts that there are differential exchanges of organisms, information, energy, and materials among patches that determine the functioning both of individual patches, and of the entire patch mosaic. Finally, the mosaic or field can change through time, and this will have its own significance for processes in the urban ecosystem. This of course, is an instance of the fundamental idea of ecology—in particular, landscape ecology (Turner et al. 2007)—that spatial structure or pattern reciprocally interacts with process or function. This remains a key area of inquiry in many realms of urban systems structure, especially those focusing on entire urban mosaics and not just on the green and blue spaces within cities, towns, and suburbs (Pickett et al. 1997).

Second was the variable source area from hydrology (Black 1991). This hydrological model was a powerful way to operationalize watershed theory. Variable source area addresses the existence of source and sink areas, and the role of flow paths over and through substrates as the functional connections in watersheds (Band et al. 2000, Miles and Band 2015). It can be applied across nested catchments, and so has a clear hierarchical structure that we hypothesized could have biological and social implications (figure 2). The variable source area approach can be integrated with the shifting, steady-state approach from ecology (Bormann and Likens 1969) and social area approach from social sciences (Shevky and Bell 1955) to explore the physical–ecological–social differentiation and dynamics of urban watersheds (Grove and Burch 1997). This is a clear link between the biological, physical, and social realms in BES in particular, and in urban science in general.

Finally, social structures in space can also be modeled as nested hierarchies. Social heterogeneity has been a key theoretical tenet since the origin of American social science (Park and Burgess 1925, Wirth 1945). It remains a fundamental principle of urban social science, although the hypotheses about its role differ from the pioneering Chicago School (Gottdiener and Hutchinson 2011, Judd and Simpson 2011). The demographic, economic, and institutional features of the Baltimore urban ecosystem differ from the scale of households through associations, through municipalities, and on to intergovernmental

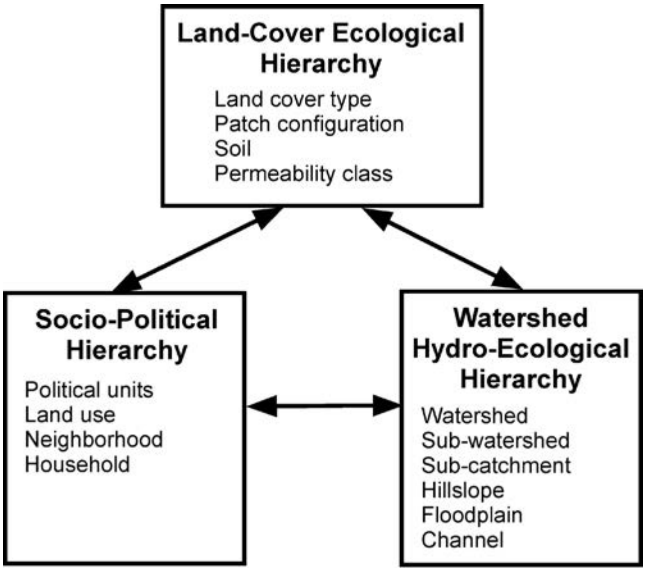

Figure 2. Three conceptual hierarchies employed at the initiation of the Baltimore Ecosystem Study.

compacts, for example. The human ecosystem model of Machlis and colleagues (1997, Burch et al. 2017) was a theorization of the ideal content of the social structures we might encounter in Baltimore. Although the model divides the human ecosystem into subsystems of critical resources, social resources, and social responses, each of which is connected to the others, we elected to label this specific conceptual tool a *framework* because it emphasized content and did not hypothesize specific flows of influence, power, or resources, and because it had the familiar theoretical structure of nesting specific mechanisms or constraints within more general mechanisms or processes (Wu 2013). These features are common to theoretical frameworks of biological and other theories (Pickett et al. 2007, Scheiner and Willig 2011). Such nested frameworks identify the components that can be chosen to construct specific mechanistic models.

The human ecosystem framework was crucial in educating the biological and physical scientists in BES about the complexity of the social half of the Baltimore ecosystem. Rather than the previous simple reliance on human population density, or aggregate demographic data about individuals, greater depth was required to expose the role of institutions, norms, social identity, and the like (Machlis et al. 1997). Such concepts became increasingly important for suggesting explanatory and predictive variables for outcomes of environmental interactions.

An important feature of these three bridging theories—hierarchical patch dynamics, variable source area, and the human ecosystem—was that they could all be deployed as nested *spatial* hierarchies, so that measurements could be matched at appropriate scales (figure 2). Although difficult, this was an important frontier challenge for urban ecology in the late 1990s. The hierarchical nesting helped guide colocation of biological, social, and hydrological measurements in order to facilitate integration. Colocation of measurements and practical application of concepts is a key tool for integration (Grove et al. 2015).

Theoretical growth in the first decade

Although our initial spanning theories of patch dynamics, variable source area, and sociospatial heterogeneity provided an effective start, opportunities and needs to refine the BES theoretical repertoire rapidly became apparent (Pickett et al. 2008). One stimulus was empirical surprises from our lengthening data sets. A second stimulus was the inadequacy of existing land use or land cover classification to reflect contrasts we observed and hypothesized as functionally important in Baltimore. Third, the richness of social structures and processes became more obvious. Fourth, an examination of the expected patterns of environmental inequity led to extensions of the theory in that realm. Finally, and most importantly, these expansions could be summarized in a new articulation of the human ecosystem concept that was compatible with Tansley's (1935) fundamental definition of an ecosystem that is familiar throughout ecology. We present the surprises and novel insights from BES along with the subsequent development of urban theory each suggested in the next section (figure 1).

Unexpected riparian function. Watershed theory was already a successful transfer to Baltimore, as was mentioned above. However, certain empirical models about watershed function that originated from rural situations failed to materialize in city and suburb (Groffman et al. 2003). This was most conspicuous for the process of denitrification in urban riparian zones. Simply put, Baltimore's urban riparian zones did not convert soluble nitrate to nitrogen gas, as had so often been observed in forested, agricultural, and pastoral landscapes (Groffman et al. 2002, 2004). Investigation to understand this surprising result discovered that the alteration of hydrologic flow paths in urban riparian zones had robbed these zones of the anaerobic conditions that denitrification requires. Piped stormwater bypassed urban streamsides, and in combination with rapid runoff from the city's impervious surfaces, resulted in severe downcutting of urban stream channels (Walsh et al. 2005). This stranded the former floodplains well above the water table.

Together, these urban conditions resulted in a hydrological drought in the riparian zones and impaired nitrogen retention. Because the rural observations suggested that riparian revegetation in urban areas could reduce nitrogen loading from urbanized areas to the Chesapeake Bay (National Research Council 2002), a new model of urban riparian nitrogen dynamics was needed. This new model fit within the broader biogeochemical theory of control of watershed nitrogen dynamics and suggested new strategies for distributing riparian function throughout the watershed (Groffman et al. 2003, Cadenasso et al. 2008).

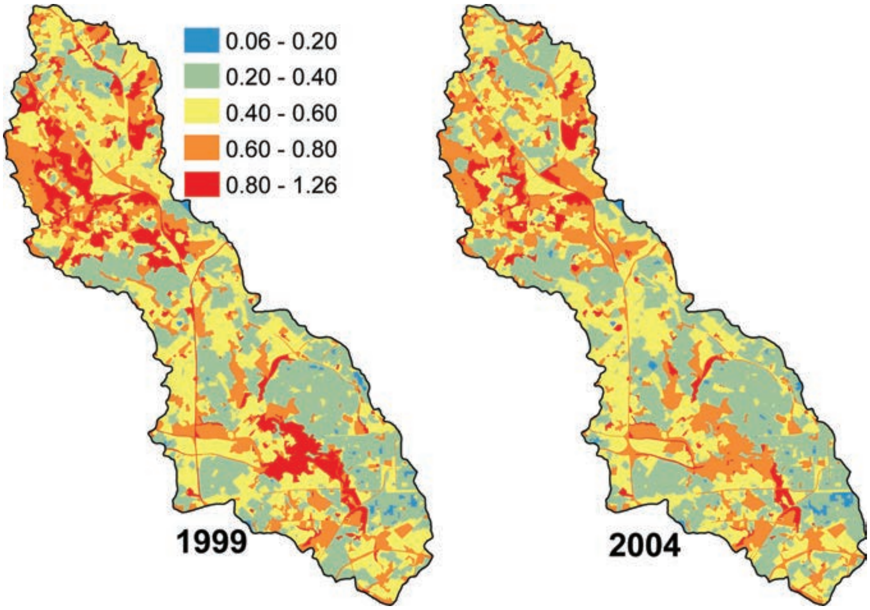

Figure 3. Mean dissimilarity of focal and neighboring HERCULES patches between 1999 and 2004. The shift from warmer to cooler colors illustrates increased homogenization of the urban landscape over time.

Hybrid urban land cover. The second example of a first decade theoretical refinement is in the area of land use or land cover. Urbanists have theorized the significance of spatial heterogeneity in cities and towns for a long time (Shane 2005). When we first began work in Baltimore, standard land classifications based on the Anderson and colleagues (1976) system were frequently used by researchers as a base layer for describing urban structure. However, because BES focused on linking urban structure that included both built and nonbuilt features to ecological and social function, we found these classifications lacking. Even the expanded classifications that added detail such as the different densities of residential areas, or simply increased spatial resolution, did not address many of the contrasts we hypothesized to be important for ecosystem function (Cadenasso et al. 2013). For example, residential classification said nothing about the presence or cover of trees and shrubs, or grass and herbs, or even pavement. This limitation reflected the fundamental assumption in earlier classifications that biological covers were distinct and spatially separable from the various built covers (Cadenasso et. al 2007). Furthermore, the conflation of cover and use made it difficult to deploy standard urban land classes as independent variables in our ecological analyses.

To compensate for these shortcomings in the standard urban land classifications for the purposes of our structure–function investigation, and for acknowledging the hybrid biophysical and social origin of urban land covers, Cadenasso and colleagues (2007, 2013) created a new classification system. This system, labeled High Ecological Resolution Classification for Urban Landscapes and Environmental Systems (HERCULES), makes different theoretical assumptions than the Anderson-based systems. In addition, the high spatial resolution of the aerial imagery (less than 1 meter) allowed assessment of the fine scale biophysical–social hybridity so conspicuous on the ground in Baltimore and other cities (Shane 2005). However, the real contrast with Anderson-related classifications is not *spatial* resolution, but the theoretical approach of the new system to discriminate patches on the basis of various combinations of built elements, the nature of the ground surface, and vegetation life form in each patch. That is, HERCULES employs a finer *conceptual* resolution on the basis of the three dimensions of the classification, and considers patches to be hybrids of the three cover elements. Using these three dimensions allows great flexibility in detecting patch types because each dimension can be measured individually depending on the research question. For example, patches with high tree cover can be selected independent of the amount or type of buildings present. Therefore, patches can be aggregated to address specific questions, issues, or scales of comparison.

A periodic table has been generated to organize patch types on the basis of combinatorics in the three dimensions and on different degrees of dominance or codominance of the cover elements (Marshall et al. 2020). Such a periodic table provides a theoretical structure that is being explored as a template for comparison across cities and over time (figure 3). Although the HERCULES system can be used in individual cities, the periodic table suggests that HERCULES can be used as a comparative tool among places and over time in urban research.

Characterizing the social structure of a postindustrial city. Early theoretical advances were also necessary in the social domain. In particular, three improvements were required: improvement of the characterization of social groups, incorporation of non- or postindustrial phases in urban change, and the importance of institutions and their networks.

The first social refinement was to apply a new method for quantifying social groups. Traditionally, race, religion, ethnicity, education, and wealth have been used as the common social categorizations. Many of these emerge from the theory of cities as industrial production centers, and are intended to describe the labor pool, human capital, and social capital that can be brought to bear to create wealth (MacLeod 2011). As certain cities evolve a postindustrial status, different criteria may provide a more appropriate way to theorize the social aspects of urban systems. Postindustrial urban systems depend on service and consumption economies, emphasizing entertainment, convenience, and leisure activities.

Furthermore, demographic shifts in some societies make medical institutions and geriatric care more important than the institutions of production. The shifts in power from old urban cores to emergent suburban nodes are also a part of the postmodern or postindustrial dynamics of urban areas (Dear and Flusty 1998). This multifaceted shift has been underway in Baltimore and has been driven by global and regional changes in employment, housing, commerce, and investment since the end of World War II.

Characterizing social structure in a postindustrial city such as Baltimore highlights broader needs for improved methods for assessing social structure. Social theory relevant to postindustrial cities suggests that such theory must address cities that are on a trajectory that does not include an industrial phase. Many cities, especially in the Global South, or in East Asia, are developing without an industrial phase. Social differentiation based on livelihoods in service and consumption sectors, which allowed refined understanding of lifestyles that guide people's environmental interactions, are important for understanding nonindustrial cities as well as postindustrial cities (McHale et al. 2013, 2015). We hypothesized that two social models would be particularly valuable for exposing human–environment relations under changing urban structure.

The first social model is a tool to describe how people and neighborhoods cluster by lifestyle (Shevky and Bell 1955). Lifestyle documents who people associate with, how they spend their leisure time, what kinds of neighborhoods they seek out, and what types of consumption behaviors they pursue. Such choices can have major environmental impacts, affecting purchases of automobiles, fuel use, house and household size, yard maintenance, and the like. The second conceptual tool is a specific hypothesis that many of people's environmentally relevant land management decisions are made to reinforce their membership in particular social groups. This theorization recognizes that people's place in actor networks may be driven by symbolic as well as by, or in opposition to, straightforward economic decisions. This is called *the ecology of prestige* (Grove et al. 2014). These theoretical refinements add mechanistic detail not highlighted in the original human ecosystem framework (Machlis et al. 1997). They show the operation of social status as a driver of ecological decisions distinct from population, education, wealth, race, and the other standard demographic descriptors.

Social expansions of BES theory also required attention to institutions. Ecologists needed to better understand the broad conception of *institution* held by social scientists (Crawford and Ostrom 1995). In particular, how institutions reflected and used different kinds of social norms or rules, how they changed through time, and how they interacted with each other, were important urban processes unseen by most ecologists. Institutional structures and decisions are major drivers of the urban changes that ecologists are interested in. An empirical exploration of this important theory in BES was the survey in 1999 of environmental stewardship organizations in Baltimore (Dalton 2001). Identifying this kind of data set as a core for BES positioned the project to ask how the network of environmental organizations changes through time, and whether that change is based on local or regional ecological knowledge, external policy forcing, knowledge of environmental hazards elsewhere, or other drivers (Romolini et al. 2013). Identifying this area as a core research topic clearly integrates the area of social network analysis as a new theoretical domain into the project as well.

The role of legacies and amenities in environmental justice. The fourth case of theoretical surprise and revision came in the area of environmental inequity and environmental justice. This important area of analysis originated because of the concerns of activists and scholars about the harm by environmental hazards visited on impoverished or minority communities (Bryant 1995, Taylor 2000). Spatial correlations between race and class with toxic waste sites, contaminated industrial brownfields, or activities generating harmful fumes or particulates were by the 1990s commonly documented. Research in Baltimore City showed a contrary pattern, however, in which working class whites lived closer to the EPA's toxics release inventory sites than African-American communities (Boone 2002). Ironically, the pattern still reflected racial segregation in Baltimore's past, when white workers were permitted to live nearer to factories or portside jobs than African Americans. This study showed that the history of social exclusion was an important explanatory process unavailable to strictly correlative studies. This conclusion was reinforced by a pioneering process-based study of environmental inequity. Lord and Norquist (2010) examined the records of requests and outcomes of environmentally sensitive zoning variances over time in Baltimore. They discovered that in the past, when Baltimore was a majority white city and African-Americans were largely segregated in specific neighborhoods, environmentally negative zoning variances were granted disproportionately in those minority neighborhoods, while at the same time being denied in white neighborhoods. This pattern only began to shift as the citywide proportions of whites and African-Americans changed. Both of these examples helped bolster and refine the theory of environmental justice (Cadenasso and Pickett 2018).

BES research into differential hazards visited on disempowered neighborhoods and on African American communities was complemented in BES by the recognition that environmental amenities and white privilege could also be sources of injustice (Boone et al. 2009). In the decades before Baltimore City demographics shifted toward a majority of African Americans, access to parks and golf courses was denied to these communities (Wells et al. 2012). An additional advance in the theory of environmental justice as applied in Baltimore was the recognition that an amenity identified by academicians or well-meaning managers might not be perceived positively by all residents. For example

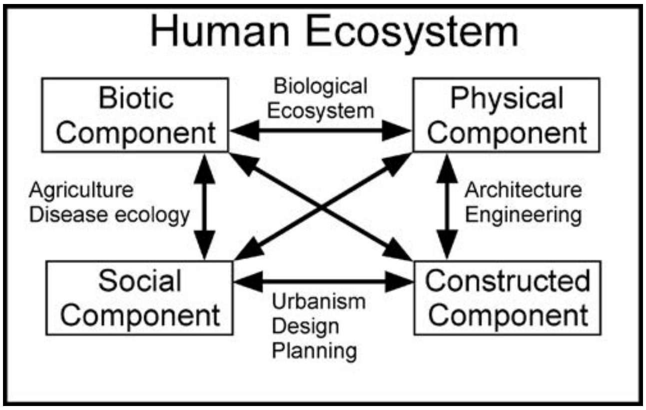

Figure 4. Human ecosystem as an expansion of the biological ecosystem concept. To the traditional components of biota and physical environment, the human ecosystem adds social components in all their richness, and the built environment including the reshaping of the land surface, built structures, engineered infrastructure, and various technologies. The human ecosystem includes all the two way interactions, each of which is labeled by examples of relevant disciplines.

some communities of working class whites did not want street trees planted in front of their houses (Buckley 2010). Similarly, minority communities can be wary of street trees because of perceptions about a relationship of trees to crime (Troy et al. 2012), to mosquitoes (Biehler et al. 2018), or fears that they leverage gentrification and displacement (Battaglia et al. 2014). The complexity of the patterns and processes of environmental justice suggests that this often practically motivated concern also has theoretical content (Pickett et al. 2011b).

An expanded view of the ecosystem. These first-decade advances in theory relevant to BES were summarized in a new articulation of the ecosystem concept that made it explicitly applicable to urban systems. Ecosystems have traditionally been described to consist of a biological complex interacting with a physical complex in some part of the Earth. Importantly, when Arthur Tansley (1935) proposed this definition, he spent a great deal of time discussing the significance of people in that context. Indeed, in a quote that has become iconic, he referred to people “as an exceptionally powerful biotic factor” (Tansley 1935:303). This encouraged us to extend the ecosystem concept explicitly to humans (Cadenasso and Pickett 2008). If the original Tansleyan ecosystem concept required a biological and a physical complex, and he accepted people as ecosystem actors, why not incorporate people as social or institutional beings parallel to the biota? Likewise, why not consider the built and constructed components of urban areas to be parallel to the topography and the physical “state factors” (Chapin et al. 2011) that affect resource availability, environmental stress and regulatory factors, and other aspects of habitat structure (Pickett and Cadenasso 2009)? Although the social and constructed factors could technically be included in the two original complexes that Tansley identified, the advances in BES theory emerging from the first decade of the project can be signaled and summarized conceptually by specifying four interacting system components in a specified volume of the Earth (figure 4). Like the original definition of ecosystems, the human ecosystem is a theoretical structure that must be applied using specific models, with their stated boundaries, temporal and spatial scales, networks of interaction, and mechanisms of feedback (Cadenasso et al. 2006a). The specific boundaries and content of an operationalized urban ecosystem model are chosen by researchers to reflect their scientific goals, or to reflect administrative boundaries for policy and application. The definition does not judge an ecosystem independent of a model that specifies certain outcomes. It certainly does not judge cities a priori as defective systems.

Theoretical advances in the second decade

A part of the guiding philosophy of BES has been to always seek new perspectives, invite new collaborators, and explore the theoretical connections that those novelties represent (Pickett 1999). Although not all opportunities have taken root, there are some notable successes. Perhaps not surprisingly, the number of researchers and disciplines increased in the second decade (2007–2017) of the project compared to the first. The continued evolution of BES theory beyond the core focus areas of the LTER program emerges as a theme. Because much of this work is ongoing, and the theories still in flux, we describe it only briefly in the present article, presenting ten examples. The examples share two features. They address various aspects of interaction among socially generated components and biophysically generated components of the Baltimore urban system. In addition, they express one or more of the dimensions of complexity: spatial, organizational, or temporal (sensu Cadenasso et al. 2006b, and explained further below). The examples of the second-generation BES theories presented in the present article (figure 1), although not exhaustive, show the evolution of thinking generated by a long-term research platform (Grove et al. 2013). During the second decade, the approaches of BES coalesced into the Baltimore School of urban ecology (Grove et al. 2015, Cadenasso and Pickett 2019, Pickett et al. 2019). Although labeled by its place of origin, a school is a conceptual system, a methodological toolkit, and a professional network that is widely applicable (Judd and Simpson 2011).

A multidimensional theory of complexity. As BES grew theoretically and empirically, it became helpful to organize our thinking around complexity (e.g., Liu et al. 2007). Cities and urban areas are now widely viewed as complex, adaptive systems (Moffat and Kohler 2008, Merrifield 2014). This means that urban systems have multiple interacting components and processes, that the individual processes and

Table 2. Relationship of the examples of theory evolution in the third decade of BES to the three dimensions of complexity: Space, organization, and history.

Theoretical advance	Spatial complexity	Organizational complexity	Temporal complexity
Engineered stream continuum	Altered connectivity in urban watersheds, burial of headwater streams, increased impervious covers	Overconnectivity of stormwater flows, altered stream hyrdographs	Legacy of stream downcutting and water table depth
Source or sink	Nitrogen retention, mosquitoes, biodiversity	Nitrogen versus piped versus septic waste regulations. Mosquitoes and differential management among neighborhoods	Mosquitoes and seasonal patterns of container water content based on ambient versus management patterns
Metacommunity	Fragmentation, vacant lots	Local versus regional controls	Human management legacies
Trait versus taxonomic diversity	Management gradients and disturbance	Taxonomic hierarchy, functional trait effects, criteria of human choices	Horticultural fashions, histories of abandonment
Biotic potential and parcels	Property regimes, parcels versus rights-of-way, configuration	Management regimes and property regimes	Histories of public and private investment
Housing market theory	Leapfrogging, suburban fragmentation	Differential regulatory impacts	
Markets and amenities or disamenities	Nonuniform distribution of amenities or disamenities	New models of housing “market” required under high vacancy	
Adaptation of institutional networks	Governance networks have spatial anchors	Policy changes affect structure of governance networks	
Dynamic heterogeneity	Heterogeneity template as a causal structure	Simultaneity of biophysical effects and human or institutional perceptions, new concept of coproduction	Lags and legacies in earlier spatial templates on later transitions
Urban homogenization	Coarse scale comparison among cities or regions	Impact of shared human culture, regulation, economy on urban ecosystems across biomes	

their interactions may be nonlinear, that there are indirect effects, lags, and historical contingencies, and that there is not necessarily an equilibrium end point to trajectories of change. These abstractions can be operationalized using key social–ecological features that appear in cities. To this end, Cadenasso and colleagues (2006b) proposed that ecological complexity consists of three dimensions: spatial heterogeneity, organizational connectivity, and temporal change. These dimensions can guide comparison and integration across space and time in BES (Grove et al. 2015). We use them to organize the remaining nine cases of theoretical advance (table 2).

Spatial complexity or heterogeneity increases as attention moves from individual patches, to patch boundaries, patch adjacencies, patch configuration, and finally to changes in the entire patch mosaic. At each of these higher levels of spatial complexity, the potential interactions increase and can intersect across additional scales.

Organizational complexity is a function of the increasing connections among the elements of the system that are capable of controlling its dynamics. Low organizational complexity exists when interactions are only or primarily within the basic spatial elements. Complexity of organization increases as more elements are connected or as more kinds of connections exist among patches. Connective interactions can include material, information, energy, or influence. Clearly, such interactions can affect system structure and change.

Temporal change or history as complexity increases as the time slice expands from instantaneous interactions only, to tracing interactions through time. Temporal complexity also involves such processes as time lags, legacies of past events, and indirect effects that emerge slowly. Temporal contingencies, priority effects, legacies, assembly, and path dependencies are common terms used by various disciplines to express historical complexity.

These dimensions of complexity have helped BES scientists explore the urban ecosystem as a complex adaptive system, a clear advance in contemporary science (Liu et al. 2007, Cumming 2011).

All of the remaining cases of theoretical refinement or novelty emerging from BES flesh out the role of spatial complexity and organizational complexity. In some cases they also show temporal complexity (table 2). There is no single ideal gradient of complexity that ties the remaining nine examples together, given that they address one or all of the dimensions of spatial, organizational, and temporal complexity. However, one way to link them is to examine how each represents increased complexity in the regional urban mosaic: The engineered stream continuum acknowledges the addition of constructed and managed elements to urban watersheds. Source–sink relationships among green and blue spaces acknowledge the functional complexity of connections among distinct patches in the urban mosaic with its constructed barriers. Vacant lots as metacommunity acknowledges not only spatial fragmentation but also management gradients and their origin as either top down or bottom up controls, often with lags. Property regimes—that is, the control of parcels by state, private, community, or open access—are a social and spatial complexity that determines the actual and potential structure of different urban places (Burch et al. 2017). Regulations of subdivision and zoning in different jurisdictions results in unexpected spatial complexity of suburban and periurban fragmentation. Governance networks acknowledge the complexity of how such controls are organized—for example, by different formal government agencies or civic organizations and the fact that these networks can respond to multiple drivers. Dynamic heterogeneity addresses the complexity of joint or coproduced human and biophysical reactions to events in heterogeneous space. Finally, urban homogenization addresses the interaction of human policy and management complexities with the coarser scale pattern of the contrasting biomes that cities occupy. We summarize these nine cases below.

The engineered stream continuum. The watershed concept has served BES well. However, it became clear that there were a variety of connections—and disconnections—intentionally or accidentally built into urban watersheds (Walsh et al. 2005). This advance recognizes the increased spatial complexity in urban areas that goes beyond the idealization of the river or stream continuum concept originally developed for wild watersheds (Vannote et al. 1980). BES researchers added the infrastructural contingencies that characterize urban watersheds to theorize an “engineered urban watershed continuum” (Kaushal and Belt 2012). The engineered stream continuum identified the conditions that differentiate urban streams as transporters versus transformers of materials, determine the controls of the nitrogen cycle discovered in the first decade, and shift how urban streams process carbon due to increased temperatures or other novel conditions because they are embedded in or altered to fit urban conditions. The role of impervious surfaces on increased freshwater salinization was documented in the first decade (Kaushal et al. 2005). However, the engineered stream continuum allowed understanding how geochemical processes such as weathering of impervious surfaces—the urban “karst”—influenced water quality over time, contributing to urban evolution of the Freshwater Salinization Syndrome (Kaushal et al. 2014, 2017, 2018).

Multifaceted source–sink relations. The synthesis of patch dynamics and the variable source area has evolved in BES. Focusing on source–sink relationships addresses the organizational complexity that can exist in urban patch mosaics. Researching source–sink interaction also seeks to discover whether there are combinations of physical factors such as topography, social factors such as neighborhood perceptions, and ecological factors such as open space where sweet spots of nitrogen retention can be planned and exploited (Kaushal et al. 2011, Newcomer et al. 2012). Other analyses of source sink relations focus on disease vectoring mosquitoes (LaDeau et al. 2015), bird biodiversity (Nilon et al. 2009), and designs for vacant lot rehabilitation (Johnson et al. 2018). In a sense, this is variable source area analysis applied not only to hydrological flows but to other physical, biotic, social, and constructed components of the ecosystem.

Metacommunity organization. Although the biotic engine in urban ecosystems may be inconspicuous or fragmented, it remains a key aspect of urban social–ecological systems (Goode 2014). The fragmented nature of urban biota suggests that metacommunity theory is useful. In ecology, metacommunity theory is closely linked to landscape ecology and recognizes that the controls on composition and structure of a biological assemblage in a given location can depend on and influence the composition and structure of similar communities elsewhere (Leibold 2011). That is, communities may be spatially distinct, but they are not necessarily entirely discrete and isolated from one another. A group of distributed instances of a community type can differentially experience extinction, immigration, and emigration, shifts in dominance, or shifts in such structural characteristics as canopy layering (Swan and Brown 2011, Swan et al. 2016). These community characteristics can be affected by the movement of individuals, genetic information, and organismal signals among the communities. Because of spatial distance, physical or biological barriers, and the differential distribution of inhospitable territory, different instances of the community may be affected differently by the combination of their internal dynamics and the relationships with other similar communities. Because urban areas provide a plethora of barriers and ecologically inhospitable territory because of infrastructure, buildings, altered environmental stresses, and direct human intervention (Pickett and Cadenasso 2009), metacommunity as a theory of differential influence among fragmented communities can be a significant contribution (Swan et al. 2016).

Trait versus taxonomic diversity. Growing attention is being paid to the diversity of traits of organisms, because evolutionary and ecological theory suggest that they should deeply influence the role of organisms in ecosystems and landscapes (Nordbotten et al. 2018). In urban ecosystems, traits may take on additional significance: People may select or filter plants and animals they wish to include or exclude in urban systems on the basis of their traits. Gardeners, arborists, park managers, urban designers, and so on, may choose plant materials on the basis of characteristics that ecologists would consider traits reflective of life cycle, reproduction, dispersal, establishment, growth, and stress tolerance (Swan et al. 2016, Johnson et al. 2018). Consequently, the active and sometimes fashion-based decisions of people concerning organism traits needed to be applied when understanding the generation and function of biodiversity in urban ecosystems. Combining knowledge of traits with the ability to characterize gradients of the intensity of human management is a new theoretical integration (Swan et al. 2011). Management gradients may technically exemplify continua of disturbance, but the focus on management highlights the human and social complexity of management regimes.

Biotic potential and property regimes. A tacit assumption of planning for green infrastructure in urban ecosystems is that space not occupied by buildings or streets is in fact available for planting trees or for other interventions that manage biodiversity or support urban agriculture and gardening (Grove 2009). BES research exposed the limitations of this assumption by combining information on building footprints, existing tree- and grass-dominated vegetation, and property parcel boundaries as overlapping, high-resolution land cover layers (Locke et al. 2013). When compared with the Baltimore City plans to double urban tree canopy by 2030, it became apparent that there was not enough land in public rights-of-way and parks to accommodate the new trees required. Because roughly 70% of the land in the city is in private hands, private land holders would have to be engaged in meeting the tree planting goals. Furthermore, comparison of the parcels and neighborhoods most lacking tree canopy revealed distinctive racial and economic features of those neighborhoods. Because of the importance of green infrastructure for providing ecosystem services (Zhang et al. 2017), and because of the different experiences of wealthy and impoverished neighborhoods with trees and other green spaces (Battaglia et al. 2014), combining property regimes, social differentiation, and assessments of biotic potential is a practical as well as a theoretical advance (Schwarz et al. 2015). Belowground conflicts with built infrastructure adds additional complexity (Rouse and Bunster-Ossa 2013).

Novel housing market theory: Contrasts within the metropolis. The theory of urban land rents or bid rents is a classic set of economic propositions to explain the distribution of various land uses with distance from urban cores (Irwin et al. 2009). Bid rent theory assumes that land use decisions are driven by price, and that markets identify the relevant quality of land in different locations. Furthermore, competition among bidders recognizes these differences in quality, which may include such location-specific factors such as transportation costs, materials, inputs for production, and infrastructure. Bid rent theory also assumes that amenities such as climate and soils are uniformly distributed. BES data show that the assumption of uniformity is incorrect in our urban system (Irwin et al. 2019).

Over its long history, bid rent theory has been modified by many factors, such as labor, and speculative behavior in periurban agricultural areas. BES extends the testing of bid rent theory by taking explicit account of heterogeneous ecological structures and processes throughout a metropolitan area. A data set of nearly 60,000 housing transactions from 1960 to present was constructed to test refined bid rent theory (Irwin et al. 2019). Adjacency to conserved open land enhances transacted prices of suburban housing, for example (Irwin 2002, Irwin et al. 2014). These insights show the increased spatial complexity that contemporary urban bid rent theory must deal with.

In addition to identifying environmental features that act as amenities and disamenities, the application of this theory in BES examines the unintended negative effects of environmentally motivated regulation of subdivision size and density, of countywide zoning regulations (Wrenn and Irwin 2015), and spatially correlated spillover effects of amenities and regulations. Stormwater detention basins were shown to reduce housing value as an unintended negative spillover effect (Irwin et al. 2014). Unintended regulatory effects are also exemplified by the fact that regulations aimed at reducing impact of large subdivisions actually stimulate fragmentation because of proliferation of small subdivisions (Irwin et al. 2019).

An untested assumption of bid rent theory in Baltimore is that land use decisions in the urban core and suburban areas constitute a single market. However, the urban core does not participate in a unified metropolitan housing market. This is because deindustrialization and population loss have resulted in massive vacancy, abandonment, and demolition. Consequently, the classic transaction-based modeling of housing markets is impossible in many core city neighborhoods (Irwin et al. 2019). Therefore, new models are being developed to extend and modify the theory. These new theoretical models explore complexity in the form of alternative measures of investment for underused or vacant properties. Because shrinking cities exist in many industrialized regions and countries (Haase et al. 2012), this theoretical refinement will be widely relevant.

Adaptation of institutional networks. Governance can be understood as involving dynamic networks over time; these networks can structure power through differential flows of information, knowledge, and other resources; networks respond to and create spatial heterogeneity; and governance networks can be crucial to understanding and fostering transition to more sustainable cities (Muñoz-Erickson et al. 2017). The complexity of governance can be studied through institutional network theory, which provides new views of the structure of environmental networks. Analysis of the stewardship network in the Gwynns Falls watershed (figure 5) revealed a shift from 1999 to 2011 toward a less centralized and more distributed network (Romolini et al. 2016). The shift also showed a decreased role of federal and state agencies and a concurrent increase in the roles of city agencies and local nonprofits. Over time, the number of actors in the stewardship network increased with the inclusion of some that were not traditionally associated with environmental stewardship (Romolini et al. 2019). For example, the number of nonprofit organizations concerned with the environment increased by the second survey. Many of these new organizations focused on social justice or community revitalization. Such changes may be partly attributable to the 2007–2009 development of the Baltimore Sustainability

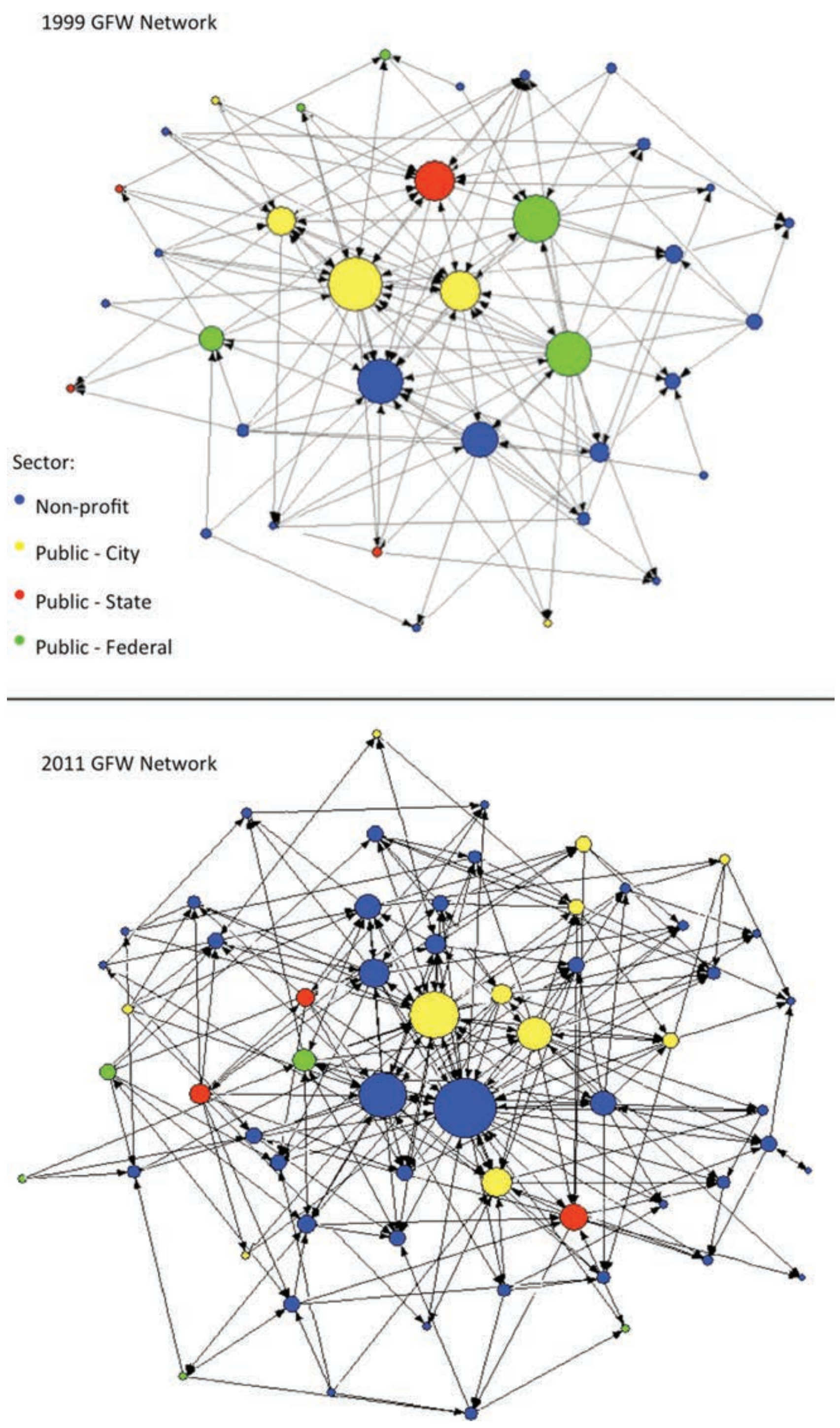

Figure 5. Networks of environmental governance organizations in the Gwynns Falls watershed, Baltimore, in 1999 (top) and 2011 (bottom). Blue represents not-for-profit organizations, yellow represents city agencies, red represents state agencies, and green represents federal agencies. Adapted from Muñoz-Erickson and colleagues (2017) under a creative commons license.

Plan, which launched the Office of Sustainability through a highly publicized community engagement process and the purposeful connections between environment, economy, and equity.

Data on how organizations receive information regarding stewardship showed Baltimore's network to be highly centralized, meaning that a small number of organizations were the main information sources for the rest of the network. However, further analysis of network centrality showed that the most well-connected organizations were not necessarily the more influential ones. In addition, 12% of the stewardship organizations were not at all connected in the network (Romolini et al. 2019).

New theoretical questions are emerging about the nature of events that stimulate network change. For example, are gradual or pulsed changes more important? How does the role of external policy directives compare with more locally identified issues? How effectively does the network account for environmental and social equity? These theories are embedded within a larger concern with ecological adaptation and resilience along with mechanisms of joint environmental, economic, and social aspects of sustainability. The variety of concerns that governance networks may respond to is an expression of organizational complexity.

Dynamic heterogeneity. This theoretical advance revisits the original theory of patch dynamics and its application of the principles of ecology that reflect the fundamental role of spatial heterogeneity (Turner et al. 2007, Scheiner and Willig 2011). Dynamic heterogeneity retains a focus on space, but emphasizes two new aspects of complexity (Pickett et al. 2017). It assumes, first, that heterogeneity is coproduced by social and biophysical processes and, second, that the social–ecological heterogeneity at any given time serves as a template that helps shape changes in heterogeneity through time. Coproduction is itself an emerging concept that goes beyond separate but coupled social and biophysical systems as a way to understand urban systems (Rademacher et al. 2018), and is thus an advance toward complexity. Although coproduction has been implied by some frameworks for social–ecological systems (e.g., Redman et al. 2004), it is worth making that joint process explicit. Biocultural diversity in cities (Vierikko et al. 2016, Celis-Diez et al. 2017) is a parallel line of thought to the social–biophysical coproduction of the city (Rademacher et al. 2018) and to biocultural conservation in remote areas (Rozzi 2012). Coproduction is a particularly appropriate concept for identifying hybrid mechanisms behind the social–ecological systems structure and function that BES now employs. The emphasis of Grimm and colleagues (2016), highlighting the role of technology while also identifying hybrid mechanisms, reinforces this conception, and has spawned the term social–ecological–technological systems. Understanding how heterogeneity in urban systems emerges and how it changes can now use coproduction to acknowledge and discern the entangled mechanisms of biophysical and social change. Such a conception is quite different than the ratchet of feedback from social drivers at one time, leading to biophysical outcomes at a subsequent time, which will later invoke new or altered social drivers, and so on (Rademacher et al. 2018). The theory of dynamic heterogeneity can expose the virtually simultaneous operation of human perceptions, actions, and biophysical processes. Each of these can act as both a driver and an outcome over very short time intervals. Coproduction as illustrated by dynamic heterogeneity can also inform the application of disturbance theory to urban systems (Grimm et al. 2017), because disturbance is an important agent of heterogeneity in ecological systems (Peters et al. 2011).

Urban homogenization. An early hypothesis that emerged in BES has evolved into a more comprehensive research theory. Pouyat and colleagues (2015) proposed that cities in contrasting climates would come to have similar levels of carbon, pH, and other properties in their soils because of similar aesthetic and land management choices. This idea of urban convergence has been expanded to ideas about ecological homogenization where urban ecosystems in different regions are more similar to each other than the native ecosystems that they replaced. Observations across six cities in the United States, representing a wide variety of native biomes have quantified ecological homogenization in plant communities, soil variables related to carbon and nitrogen cycling, microclimate and hydrography (Groffman et al. 2017a). This homogenization is driven by common human values for aesthetics and low maintenance requirements (Larson et al. 2016). Convergence and homogenization have regional and continental scale implications for water quality, biodiversity, carbon sequestration and other ecological functions of both highly and less intensively managed or natural ecosystems (Epps Schmidt et al. 2017, 2019). More generally, convergence and homogenization represent truly integrated socioecological theories that should be useful to understanding the structure and function of ecosystems across the world and become a fundamental component of sustainability theory, science, and practice.

Futures of urban theory. Urban theory stands to mature considerably in the future. Indeed, several syntheses have addressed the opportunity, need and shape of the urban science of the future (Childers et al. 2015, McPhearson et al. 2016, Groffman et al. 2017b, Acuto et al. 2018). In the present article, we point to three areas in which theoretical development has the potential to go beyond the empirical and conceptual insights summarized in this article. These are not the only important ways forward, but we believe they have considerable theoretical potential and utility.

The urban realm of the Earth is changing rapidly. McHale and colleagues (2015) identified four overarching global urban realities. Cities are diffuse (i.e., no longer structured or acting as discrete entities), complex in both space and organization, connected regionally and globally, and diverse, that is not following any single development pathway, but differing from one another in internal and regional configurations.

Three frontier theories can operationalize these global realities in particular places, or provide mechanisms and explanations for the realities: the metacity, the megaregion, and the continuum of urbanity.

Metacity theory describes urban areas at any scale as shifting mosaics of biophysical environment; human social, institutional, economic, and political structures; and built and constructed urban fabric (McGrath and Pickett 2011, McGrath and Shane 2012, McGrath 2013, Pickett et al. 2013, Zhou et al. 2017). A grand application of patch dynamics to social, ecological, and technological processes, the metacity provides a way to visualize and project urban structures and processes across space and through time. Notably, this use of *meta* is akin to the metacommunity or metapopulation approaches in ecology and illustrated briefly for Baltimore earlier in this article. It does not use *meta* as in some United Nations Habitat documents to mean cities of greater than 20 million. We feel the process definition of *meta* inspired by ecology is particularly useful as a theoretical framing.

The second emerging frontier theory for understanding and designing the cities of the future is the urban megaregion. This theory must grow with the increasing regional nature of cities (Regional Plan Association 2007, Angelo 2017, Brenner 2014). Cities are now parts of urban agglomerations—that is, clusters of cities of various sizes. Megaregions include agglomerations of large cities but also embrace towns and villages as a part of the Earth's urban estate. Tied together by vast transportation networks and virtual communications, megaregions bring the benefits and burdens of urban life to the countryside and to small settlements that increasingly reflect urban values, wealth, and employment outside the natural resources sector (Seto et al. 2017).

A third theoretical realm that builds on the global urban realities is the continuum of urbanity. Following the arguments of social scientists, urbanists, and historians, the continuum recognizes the entanglement of lands and lives in rural and wild places with those in places that are more culturally and structurally urban. This theory, only recently introduced (Boone et al. 2014) and, as yet, still developing, can provide a mechanistic understanding of regionalized and global urban change. Any location in a regional or even global urban network has both biophysical and cultural features. That is, virtually all places combine natural and human artifacts and processes (Vierikko et al. 2106). Thus any site can be conceived to be located along a continuum of urban–rural characteristics. Note that this does not refer to a literal transect on the ground.

The continuum is valuable as a theory because it hypothesizes that any individual place will be characterized by some mixture of urban versus rural livelihoods, urban versus rural lifestyles, and will be connected to urban and rural places elsewhere. Amazonian forest falls to yield soybeans to feed the pigs for the growing middle class in China and other distant places (Miller 2012). The livelihoods, lifestyles, and connectivity that intersect in particular places will shape those places. In turn the nature of the individual places will likely influence the processes of livelihood, lifestyle, and connectivity that are anchored there. This theory provides an intellectual structure to explore the increasing entanglement of urban and rural places across regions and the world because of globalization.

The issues these emerging theories must confront include global changes of climate and sea, developing and changing technologies, and human migrations of opportunity or crisis (Cilliers et al. 2009, Clemens et al. 2014). In addition, these theories will struggle with of how to conceive, measure, and represent the consistently problematic relationship of humans and nature (Cronon 2003, Kingsland 2005, Steiner et al. 2016). These theories can also play a role in linking ecological understanding of urban places with such important activities as planning, design, and restoration. These links highlight the need for theories to address the pairing of environmental stress or disturbance and adaptation as drivers of change and adaptation. Although there are certainly other urban theories that will be important in the future, these three give some sense of the richness of urban theory yet to come, as well as its foundation on existing ideas and data.

Conclusions

The BES has a rich and dynamic theoretical foundation and context. Although there is a framework for general ecological theory (Scheiner and Willig 2011), no such framework exists for urban social–ecological science. The addition of social, economic, institutional, and political dimensions to the biophysical aspects of urban ecosystem structure in cities means that urban theory must extend beyond its biological roots. The initial goal of BES was to bring the perspectives of biological ecology, physical science, and social science together in an inclusive understanding of an urban ecosystem. This goal was novel enough in 1997 to be labeled the *ecology of the city*, with emphasis on *of* rather than *in*. In the absence of a unified theory for urban social–ecological systems, BES had to rely on existing disciplinary theories to link the three broad, contributing disciplines together. The three areas were represented by hierarchical patch dynamics, variable source area hydrology, and the human ecosystem framework. Long-term data sets were initiated in these important disciplinary foci but also purposefully targeting topics that intersected the three areas.

Two things happened early in the history of BES that stimulated new expansions of the theoretical foundation (figure 1). First, some empirical findings failed to confirm the expectations of the initial theories (Pickett et al. 2008). In particular there were surprises in riparian system function, a failure of the standard land use or land cover classifications to support analyses of relationships between system structure and system function, and the need to extend the human ecosystem explicitly to embrace the urban. Socially relevant theories that were added, operationalized, and tested included lifestyle clusters, the ecology of prestige, and the networked role of institutions (Pickett et al. 2011a). Together these surprises and extensions suggested that a form of the ecosystem concept could be articulated to explicitly incorporate human-originated structures, activities, and perceptions. The first decade of expansion of BES theory was signaled by the human ecosystem model template incorporating biota, physical environment, social structures and dynamics, and constructed components. This parallels the social–ecological systems conception (Folke et al. 2002), and the social–ecological–technological concept (Grimm et al. 2016).

In the second decade of the project, two things led to additional extensions of theory. One was the interdisciplinary growth of the research team. This extended the experience of members from various biophysical and social sciences to include different concerns and concepts represented by new disciplines, such as governance, economics of suburbanization, and urban design. Second, the longevity of the interdisciplinary interactions in the team became a significant facilitator. These lasting interdisciplinary interactions promoted cross-disciplinary familiarity, but they also helped establish trust within the diverse research team. Importantly, this trust also characterized the maturing relationships among researchers, educators, agency policy makers and managers, community engagement specialists, and environmental and community activists in Baltimore (Grove et al. 2015).

The richness and dynamism of theories useful in the BES has several implications. First, the empirical understanding of temporal complexity in urban ecological systems and social–ecological adaptations depends on long-term platforms for research. Given the social–ecological stresses and the need for adaptation that cities face in the near and long term futures, it is an open question for urban ecology whether there is sufficient long-term scientific capacity at local, national, and international levels. Second, although the study of urban systems is important for policy and management because such areas are growing globally and changing on all scales, it is also theoretically motivated and has produced new or revised theories that are generating new ways of thinking about urban areas and extending the scope well beyond the city (e.g., Seto et al. 2017). Novel theory and models have emerged at the intersection of the different disciplines. But novelty has also emerged in the knowledge gaps identified by environmental and social policy and management strategies (Childers et al. 2015, Zhou et al. 2017). Old theory has been successfully applied to the Baltimore ecosystem, but new theory has developed at the sutures as well. Specific models have incorporated new interactions and mechanisms, showing the productivity of urban systems as a theoretical engine well beyond their practical importance. Ecological theory is rich and evolving in urban areas, but the pursuit of the missing general theory remains a motivation for continued research.

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