Does the ecological concept of disturbance have utility in urban social–ecological–technological systems?

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Abstract. The ecological concept of disturbance has scarcely been applied in urban systems except in the erroneous but commonplace assumption that urbanization itself is a disturbance and cities are therefore perennially disturbed systems. We evaluate the usefulness of the concept in urban ecology by exploring how a recent conceptual framework for disturbance (Peters et al. 2011, Ecosphere, 2, art 81) applies to these social–ecological–technological systems (SETS). Case studies, especially from the Long-Term Ecological Research sites of Baltimore and Phoenix, are presented to show the applicability of the framework for disturbances to different elements of these systems at different scales. We find that the framework is easily adapted to urban SETS and that incorporating social and technological drivers and responders can contribute additional insights to disturbance research beyond urban systems.

Key words: cities; conceptual framework; disturbance; economic disruption; fire; flood; land conversion; legacy; model; social–ecological–technological systems; urban vegetation; urbanization.

Introduction

Disturbance has long been recognized as a crucial driver of ecological processes and has a rich ecological literature associated with it (Sousa 1984, Resh et al. 1988, Johnson and Miyaniishi 2007, Turner 2010, Peters et al. 2011). Disturbance is one of the five core research areas of the US National Science Foundation’s Long-Term Ecological Research (LTER) network and is a primary focus of research at many of the LTER sites. Although the emphasis of research may have changed over the 30 years since Pickett and White’s (1985: 7) classic book was published, their definition of disturbance is still generally accepted:

any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment

But how disturbance as a concept applies to the coupled human and natural systems of urban areas is poorly understood. Indeed, the naïve ecological habit of taking urbanization per se as disturbance does not advance the understanding of spatially and organizationally complex urban systems. There has been a general tendency among ecologists to refer to human-dominated ecosystems, cities included, as de facto “disturbed systems” and thereby to humans themselves as disturbance agents and any human activity as a disturbance (Liley and Clarke 2003, Markovchick-Nicholls et al. 2008, Buyantuyev and Wu 2010, Carreiro and Zipperer 2011, Chow and Svoma 2011, Calizza et al. 2012, Davidson and Gunn 2012, Li et al. 2012, Lin et al. 2012, Wolf et al. 2013). The issue of conflating urban with disturbance becomes clear when one adopts a view of cities as ecosystems (e.g., Pickett et al. 1997, Grimm et al. 2000), since people themselves are part of and creators of the system (McDonnell and Pickett 1993). A second challenge is especially pronounced in urban areas, but relevant to all coupled human and natural systems: That the drivers or agents of disturbance, as well as the entities upon which impacts are visited, may be physical, biotic, or social.

Our primary research question is “What is the utility of the ecological theory of disturbance for understanding urban social–ecological–technological systems (SETS), and what modifications to the theory need to be made?” There is an urgent need to unpack the concept of disturbance in order to apply it effectively to urban systems and

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develop refinements of the theory, beginning with a clear and unambiguous model of the system of interest. Such a model would address the system's spatial and temporal extent, structure, function, and dynamics. These requirements have long been recognized as key to understanding disturbance in non-urban systems (Pickett et al. 1989). Coupled human and natural systems and urban SETS clearly differ from “natural” ecosystems in many of these dimensions, however. The system model would need to include unique urban SETS characteristics such as their built infrastructure and their massive energy flows, material inputs, and waste outputs supporting the urban economy (e.g., Odum 1997, Kennedy et al. 2007, Chen and Chen 2012). Thus, the concept also must be evaluated in the context of an appropriate framework. In this paper, we will adapt the framework of Peters et al. (2011; Fig. 1), which is initiated with a clear specification of the system being disturbed, to urban SETS. We will apply the adapted framework using a comparative approach; in particular, we use insights emerging from comparison of disturbances in Baltimore and Phoenix to provide needed theoretical refinement and identify data gaps that must be filled.

**The Ecological Concept of Disturbance**

**Original definition**

In the 1970s, ecology as a whole began to move from its classical focus on seemingly intact, equilibrial systems (Simberloff 2014), to a widespread recognition of the role of disturbance in shaping populations, communities, ecosystems, and landscapes. This recognition emerged from lengthening and proliferating long-term studies, paleoecological comparisons, and observation of extreme and disruptive events (West et al. 1981, Mooney and Godron 1983, Weatherhead 1986, Grimm and Fisher 1989, Likens 1989). An early codification of this new view was the Pickett and White (1985: 7) definition stated earlier. Key elements of this definition are (1) a focus on system structure, originally expressed as three-dimensional architecture extending both above and below the substrate surface, (2) spatial and temporal discreteness of the event, and (3) alteration of environmental resources, stressors, or signals. The fundamental definition can accommodate disturbances that are exogenous in origin, as well as those that emerge from interactions from within the system of interest (e.g., Kimmins 2004). Whether or not an event—exogenous or endogenous—is considered to be a disturbance depends upon the model of the system. The same event can be considered a disturbance under a particular model of the system and not a disturbance under an alternative model of the same system. This will be more fully explored below.

**Refinements in the concept**

Since the initial codification of disturbance, it has become clear that the nature of the study system (Rykiel 1985) and the nature of the events themselves (Pickett and Cadenasso 2009) have to be better understood. As a result, the disturbance concept has undergone refinement and clarification that facilitate its application to...
urban SETS. Key features of a contemporary conceptualization of disturbance are as follows:

1. Disturbance is a structural disruption (Grime 1979, Pickett et al. 1989), conceptually complemented by recognition of stresses that disrupt system process (Grime 1979, Pickett and Cadenasso 2009) and may thereby lead to structural disruptions.

2. Explicit definition of a system, in terms of its boundaries, composition, and interactions, is key to understanding disturbance impacts (Jax et al. 1998, Peters et al. 2011), including effects over time and space.

3. A disturbance event may be characterized by its intensity or magnitude, spatial extent, duration, and timing (Sousa 1984, Roxburgh et al. 2004, Johnson and Miyashita 2007), independently of the impacts of that event.

4. Spatial and temporal patterns of various disturbances across landscapes, that is, disturbance regimes (including type, frequency, timing, spatial extent, intensity, and interactions among different event types), are important controllers of the composition and functioning of systems (Grimm and Fisher 1989, Dale et al. 1998, Frelich 2002, Sabo and Post 2008).

Here, we evaluate whether these insights concerning disturbance that are reflected in the Peters et al. (2011) framework can be applied to urban systems.

The need for system specification and disturbance mechanisms in the urban context

As ecologists have applied the concept of disturbance in an increasing variety of situations, including urban ones, it has become clear that the disaggregation of disturbance into component processes and the clear specification of system models are especially necessary. A Web of Science search (all years; accessed 20 October 2015; see complete list in Appendix S1: Table S1 and selected citations in the following paragraph) yielded 39 total papers with words “urban” and “disturbance” in the title, of which 32 are ecological papers, the earliest published in 2000. We used a very broad definition of “ecological paper,” excluding only psychology, political science, medicine, and other clearly non-ecological references to arrive at the 32 references examined. Of those 32, 26 treat the process of urbanization as a disturbance in itself, four consider effects of disturbance on an urban system, and two discuss how urbanization changes ecological disturbance regimes. Of those that consider effects of disturbances on urban systems, two explicitly considered the urban system to be a coupled human and natural system; the other two addressed the effects of human activities—hand tilling or infrastructure maintenance—on specifically urban assemblages of plants or marine species. This brief survey illustrates how urbanization and human activities are conflated with disturbance in the ecological literature.

Complex events are often labeled disturbances. However, to understand the hazards, causes, impacts, and responses to disturbance, such complex events must be disaggregated or “unpacked” (Pickett and Cadenasso 2009, 2012, Peters et al. 2011). Urbanization itself is a very complex process that confounds attribution of environmental changes in cities to one or a few specific mechanisms. Urban disturbances in the literature have included, among others, human activity (i.e., the presence of humans, Fernandez-Juricic and Telleria 2000, Fernandez-Juricic 2002, Markovchick-Nicholls et al. 2008, Orrego et al. 2009, Gonzalez-Oreja et al. 2012, Zhou and Chu 2012), land use and land cover change (Liley and Clarke 2003, Markovchick-Nicholls et al. 2008, Buyantuyev and Wu 2010, Carreiro and Zipperer 2011, Chow and Svoma 2011, Calizza et al. 2012, Davidson and Gunn 2012, Li et al. 2012, Lin et al. 2012, Wolf et al. 2013), soil disturbance (Graf 1975, Latzel et al. 2008, Brunzel et al. 2009, Trammell et al. 2011), hydrologic changes (Walsh et al. 2005, Hopkins et al. 2015), and noise (Katti and Warren 2004, Warren et al. 2006, Lowry et al. 2011, Gonzalez-Oreja et al. 2012). Although many of these uses of the disturbance concept may aid in understanding ecology in the city (e.g., effects of human presence on bird behaviors; Fernandez-Juricic and Telleria 2000), denoting the mere presence of humans as disturbance would render the concept useless in the whole-system-based study of urban SETS. In addition to defining the system precisely, we need to disaggregate the mechanisms of disturbance. We employ a framework that can facilitate the unpacking and specification required to apply the disturbance concept to urban systems.

A Framework for Urban Disturbance

System and model specification

In order to improve the understanding of disturbance in urban systems, two things are required: First is an understanding of disturbance as a basic ecological process. Second is a way to translate this process to the combined social, ecological, and technological complexities of urban ecosystems (Pickett and Cadenasso 2009). The disturbance framework presented by Peters et al. (2011) provides the ecological foundation (Fig. 1). We briefly mention both natural and urban features of disturbance that illustrate this conception. The Urban Disturbance Framework Applied will present urban cases of disturbance in greater detail.

The most fundamental requirement for studying and understanding disturbance is a model that represents or specifies the system of interest (Pickett et al. 1989). What, in other words, is being disturbed? Disturbance cannot be evaluated without a clear specification of the system and its properties that an event might affect. Specification of a system requires that the boundaries be delimited in space and time, setting the extent of the
system (Cadenasso et al. 2003). In addition, the structural components of the system must be specified. For urban systems, these will include physical, biological, social, and built components (Fig. 2). Each of these components is itself complex, as detailed in the literature on social–ecological systems (Redman et al. 2004, Pickett and Grove 2009, Grimm et al. 2013). The physical components include the air, waters, climate, and seasonal and daily cycles of regulating factors such as day length, temperature, and humidity. Biological components include the dominant humans, native plants and animals, accidentally and purposefully introduced organisms, including invasive species, and ubiquitous microorganisms. Social components include individual human decision makers and social groups ranging from households, through civic associations, through government agencies (Machlis et al. 1997). Notably, norms and regulations are important aspects of the social component of systems (Ostrom 2010, Cook et al. 2012, Larson and Brumand 2014). The built component of the system refers to the architectural structures, as well as technological infrastructure such as roads, rails, pipes, wires, and media (Shane 2011, Redman and Miller 2015, Grimm et al. 2016). Identifying the interactions, exchanges, processes, and influences that link these components completes the specification of the system. Urban systems are highly open, and massive throughput of materials and consumption of energy are typical (e.g., Odum 1997), leading some schools of thought to liken this dependence on external systems to that of a heterotrophic organism (i.e., the concept of urban metabolism; Wolman 1965, Kennedy et al. 2007, c.f. Kaye et al. 2006). Within urban systems, commuting links locations and social groups, while traffic, wires, and pipes convey resources and wastes into, through, and out of the urban system. Furthermore, information flows take the form of money, news, regulations, cultural markers, and so on (Boone et al. 2014), which are also highly open to external systems.

The specification of an urban system sets the stage for understanding what is or is not a disturbance, defined here as an event that disrupts any aspect of the structure of an urban system as specified in an explicit model. In an urban system, the removal of part or all of one of the four kinds of components of the system, or destroying the linkages among them (Fig. 2), or with the external environment, can constitute a disturbance. Fire removes or limits the use of buildings. Windstorms remove trees along streets or in property parcels. Real estate decisions replace low or small buildings with taller or larger ones. Human population decline or a decrease in management intensity or frequency can drive vacancy and perhaps ultimately demolition of housing or industrial building stock, with cascading effects on biotic communities. Disruption of supply chains from external systems can halt or slow internal processes. But strictly considered, disturbance as a structural modification can also result from adding new infrastructure, buildings, technologies, or populations to urban systems. In other words, adding a structural element can be a disruption of a system. These brief examples make the point that disturbance in urban ecosystems is not necessarily good or bad in and of itself. However, many disturbances benefit some persons or institutions, while perhaps disadvantaging or damaging others. Disturbance can be a powerful driver of environmental inequity (R Campanella 2007, Pickett et al. 2011, Boone and Fragkias 2012). Thus, the relationship of disturbance in urban systems to such things as environmental justice, cultural values, and social capacities to respond are important issues.

Once the system model is specified, the complex process of disturbance itself must be disaggregated by identifying and linking three key phenomena (Fig. 1). Following Peters et al. (2011), the phenomena of disturbance are (1) drivers, (2) mechanisms, and (3) impact. The (4) response to disturbance completes the understanding of disturbance. We describe each of these below.

Disturbance drivers
Disturbance requires, above all else, agents of potential change. The definition of disturbance focuses on agents that are initiated or change suddenly, regardless of whether they are endogenous or exogenous. In urban systems, these will be drivers that provide either pulses or presses of climatic and atmospheric force, kinetic movement of physical materials, biotic action such as consumption, chemical transformation such as fire, and social disruptions such as demographic shifts, institutional ruptures, or redirection of finances. The emphasis on onset of the events highlights that disturbance drivers change over short time spans relative to the life of the system, and the emphasis on various kinds of forces highlights that direct structural alterations of the system result from effective disturbance. Not all occurrences of a
particular kind of driver will result in system disruption. Recognizing context suggests that whether a specific occurrence results in disturbance to the specified system depends on the actual mechanisms and on the internal characteristics and broader setting of that system.

**Disturbance mechanisms**

Often disturbance is attributed to a particular disturbance type, such as flood, fire, windstorm (Fig. 1). Each occurrence of one of these types may in fact result from change in one or more drivers, and each driver implies one or more particular mechanisms by which the force is delivered to the system (Bart and Hartman 2000, Johnson and Miyashita 2007). For example, a hurricane, as a disturbance type, can include the force of the wind, tidal surges, or flooding. These are mechanisms resulting from the hurricane, generating motive force or potential for waterlogging. A given instance of a type, such as a hurricane, can thus effect disturbance in a system directly by blowing down trees, or indirectly by saturating soils and weakening the stability of tree root systems. The specific impact of a given event depends on the mechanisms that it empowers. In general, mechanisms of physical disturbance can include abrasion, combustion, compaction, erosion of substrate, deposition of sediment, waterlogging, mass movement of earth materials, and changes in resource level (Peters et al. 2011). The physical fabric of urban systems, that is, the physical and built components, can be disrupted by these physical mechanisms as well, as demonstrated by particular earthquakes, fires, tidal surges, or blowdowns of street and yard trees or patches within urban forests. For example, the same hurricane can destroy a component of infrastructure when trees fall and break aboveground electrical wires, causing power failures; blackouts may cascade through other infrastructure systems, such as water delivery systems that depend on electrical pumps. It is worth noting, however, that some built components of urban systems are specifically designed to withstand earthquake, fire, wind, and floods and even to protect other built structures and human lives from the impacts of these events. This intentional design and foresight about the possibility of disturbance is a distinctive feature of the structure of social-ecological systems, which may have analogues in the evolution of resilience mechanisms in non-urban ecosystems, such as serotinous cones of pines (Christensen et al. 1989) or dispersal adaptations of stream invertebrates (Gray and Fisher 1981).

Biological mechanisms of disturbance include those events that consume biomass or convert it suddenly from one pool, such as live leaves, to another pool, such as detritus that has been transported to a landfill. Harvesting, herbivory, and defoliation are examples of potential biological disturbance mechanisms widely recognized in non-urban systems that also apply in urban SETS. Complex human management activities result in a suite of mechanisms that are characteristic of urban systems, such as application of herbicides and pesticides, harvesting, or pruning. What specific biologically focused mechanisms of potential disturbance are relevant will, again, depend on the model of the system.

In urban systems, social disruptions must also be considered as potential types of disturbance, with associated mechanisms. If an urban system model considers the distribution of demographic identities and social structures, such a model may appropriately take human migration as a disturbance to that structure. Indeed, migration is one of the most common modes of alteration of urban system structure, but socially generated disturbances can also include demographic shifts in household size and composition, financial investment and disinvestment, criminal activities or violence, and the decision-making processes that build or destroy infrastructure. These mechanisms arise in part from the drivers of human and institutional choices. Shifts in governance, regulation, norms, and fashion can drive alterations in the social and ecological structure of urban systems as well. In all cases, whether the drivers and disturbances are physical, biological, or social, the system model dictates the level of mechanistic detail chosen. Models that define the system via general phenomena such as land cover may suggest different relevant mechanisms of disturbance than a model that examines turnover of specific parcels within a city or suburb. Hence, mechanisms can sometimes be aggregated or disaggregated as the model requires.

**Disturbance characteristics and impacts**

How each event will play out via specific mechanisms depends on characteristics of the event. Each potentially disturbing event can be characterized by its onset, duration, and release (if any; Pickett and Cadenasso 2012). The distinction between pulse and press events (Collins et al. 2011) recognizes two temporal patterns of onset, duration, and release. However, it is important to recognize that ecological events can exhibit a much wider range of combinations of onset, duration, and release, and the impact of each event will depend, in part, on its specific temporal pattern (Pickett and Cadenasso 2009). Similarly, events that change urban SETS structure may arise suddenly or gradually, be long-lived, and have a rapid or a protracted release.

Also key to understanding disturbance is assessing its impact on the structure of the specified system. Disturbance, as defined earlier, requires a qualitatively or quantitatively measurable alteration of the structure of the system as described by an explicit model. A component of the system may be removed, or a pathway of interaction between components may be removed. For an urban example, hydrologic pathways are typically altered during urbanization. Ground disturbance may result in extensive stream siltation, and streams may be canalized or buried, constituting profound physical disturbances to the system. After some duration, release occurs when
construction activities cease (Graf 1975). Yet the system identity has shifted from, for example, a gravel-bedded stream to a component of stormwater infrastructure such as a concrete flume. In this case, the system has transformed to a new state, and a new system model is required (Fig. 1). Other examples will be presented in The Urban Disturbance Framework Applied on Case Studies.

Social impacts must also be assessed in urban systems. Sometimes biophysical disturbances will entail social disruptions and these disruptions can arise from direct individual and collective decisions. Of course, loss of life is an outcome of severe disturbances like fire, flood, earthquakes, hurricanes, and heat waves. However, financial losses, loss of social capital, disruptions in networks of productive social interactions, and changes in institutional capacity can also result from disturbance. Social disturbances can be read in vacancy of commercial and residential structures and may sometimes lead to the physical disturbance of demolition and creation of vacant parcels and lots. When disturbance interacts with a social system, the implications for ethics and social equity must be evaluated.

Disturbance responses

Exemplifying social impacts has highlighted the wide variety of responses to disturbances in urban systems. Responses are conditioned by the nature of the system, that is, vulnerability of a component to a particular physical or social disruption. Earthquake effects in cities depend, for example, on the kind of building construction. Mortality from tsunamis or heat waves depends in part on the presence of warning systems and infrastructure to provide emergency shelter. Importantly, one disturbance can subsequently lead to others, for example, when a social disturbance leads to biophysical changes. Alternatively, physical disturbance can lead to social disturbance, for example, when the flooding following Hurricane Katrina resulted in abandonment and demolition of buildings in low-lying wards, caused massive depopulation of the city, and ultimately the social outcome of altered demographic composition of New Orleans (Campanella 2006, Campanella 2007). In urban areas, responses to disturbance can include natural succession, socially mediated vegetation management, alteration of zoning, revised building regulations, construction of new infrastructure or rebuilding of damaged infrastructure, or alteration in urban landscape configuration based on where rebuilding is sited or avoided. Responses may be immediate in time or space or they may be spatially or temporally lagged from the initial disturbance.

Other considerations for applying a disturbance framework to urban SETS

As in other ecosystems, the drivers, mechanisms, impacts, and responses to a given urban disturbance are to some extent conditioned by the larger temporal and spatial context of the event. The larger temporal and spatial contexts should be specified as part of the system model. The continued experience of disturbance will change system properties, and legacies of past disturbance will influence responses and processes that lead to new states. In contrast to the equilibrium theories of ecology prevailing when the ecological concept of disturbance was first articulated, theories of resilience developed by scholars of social–ecological systems (e.g., Holling 1973, 2001, Folke et al. 2004, Walker et al. 2004) hold that responses to disturbance can range widely and encompass multiple states. Our adaptation of the Peters et al. (2011) framework allows for this wider latitude in states via multiple passes through the sequence described by Fig. 1. The maintenance of essential structures, functions, and interactions that characterize a multi-equilibrium system encompasses the traditional view of steady-state mosaics of differing successional stages, for example, in a forest landscape (Likens and Bormann 1995), but also very different potential configurations of cities depending on the magnitude of impacts and the responses, particularly the social responses. Drivers and legacies that lead to the crossing of tipping points and transformation to entirely new states are also possible in this view (Childers et al. 2014).

The Urban Disturbance Framework Applied

Major historical disturbances affecting cities

In non-urban ecosystems, disturbances that are severe and extensive may have mechanisms, impacts, and responses that are distinct from smaller disturbances, which are better known (Turner et al. 1997, Turner and Dale 1998). These large, infrequent disturbances, such as the 1980 Mount St. Helen’s eruption and the 1988 Yellowstone fires, are characterized by rarity and large spatial extent (Turner and Dale 1998). Examining large events in cities may lead SETS researchers to improve their system models by identifying structures that were previously unknown or unlinked, or may motivate the construction of new models of urban SETS that have utility for other purposes. Urban disturbances with severe impacts (e.g., Fig. 3) provide opportunities for learning, even for society as a whole. To introduce the nature of urban disturbances, we use examples of major events—heat waves, flooding, and catastrophic fire—and look to a future of extreme events under climate change.

Disturbance by heat waves

Heat waves are disturbances with large impacts on urban residents lacking air conditioning and confined to sweltering buildings. The 2003 European heat wave, which lasted 2 weeks and resulted in nearly 40,000 deaths, has been called “the biggest natural disaster in Europe on
In the United States, the 1995 Chicago heat wave resulted in deaths of over 700 people, almost all of them isolated, poor, elderly residents of dangerous neighborhoods lacking social cohesion (Klinenberg 2002). This disturbance was devastating not because of its inherent severity but because of social vulnerabilities in the system: lack of social networks for those affected, and inadequate response from government. Later heat waves in Chicago did not have this kind of impact because the government was quick to provide aid to vulnerable people (Klinenberg 2002).

Disturbance by flood

Large floods deriving from locally heavy rainfall, river flows, and marine storm surges affect cities disproportionately because of the prevalence of urban development along rivers and coasts. Impacts of the flooding of New Orleans, Louisiana, in the wake of Hurricane Katrina disproportionately affected the poor. Extensive engineering modifications of the regional hydrology, the creation of infrastructure that outwardly appeared to offer protection from flooding but in fact worsened the impacts when levees were breached, and the prevalence of affordable, low-income housing in vulnerable, low-lying areas all were ways in which the region was transformed by human engineering (originally, disturbances themselves) and made more vulnerable to the impacts of the hurricane (Kelman 2003, Lewis 2015).

Disturbance by fire

The Great Fire of Baltimore in 1904 illustrates the application of the Peters et al. (2011) framework for a large urban disturbance (Olson 1980). The system state before the fire contributed to its impact (Fig. 4). Buildings in the downtown commercial and financial district, although mostly masonry, were closely packed and laden with diverse fuels. What would later be labeled the “Burnt District” included packed warehouses, lumberyards, offices, coal yards, and dry goods stores. The social structure before the fire included lax zoning and warehousing codes and a lack of national standards for fire hydrant fittings. Once the fire began, high winds accelerated its spread and freezing temperatures hampered firefighting. As the fire...
burned, help was sought from nearby cities but the non-standard hydrant fittings rendered this assistance futile. The two-day fire’s impacts were severe: Over 1,500 buildings were destroyed, 35,000 people lost their jobs, and 57 ha was burned. In 2014 dollars, damages amounted to $3.8 billion, making it one of the most costly urban disturbances in U.S. history. This destruction left a massive legacy of debris, later used as fill in extending the waterfront (Fig. 4).

Reconstruction and new regulations after the fire were promoted by social drivers—civic pride, the city’s elite pressuring for new governmental regulations, a national press seeming to blame Baltimore for its non-standard hydrants. Rebuilding was swift, and new building codes, national hydrant standardization, and zoning supported a more resilient Baltimore. This recovery process underscores that large, urban disturbances often present a window of opportunity to improve physical infrastructure, social institutions, and regulations so that a city is better prepared for future extreme events.

**Disturbance and climate change**

Today, climate change is a rising driver of disturbance, with the frequency and magnitude of today’s large disturbances projected to increase (IPCC 2012). Indeed, weather-related extreme events have increased sharply over the past decades worldwide (Natural Catastrophes 2014). Two aspects of the current system state make cities vulnerable to heavy impacts from these events. First, for many cities in the industrial world, infrastructure that is meant to protect people and property from extreme events is aging and in need of replacement (ASCE 2013). Furthermore, this infrastructure was designed for events of particular sizes and likelihoods of occurrence. However, these disturbance parameters are changing. For example, a storm surge that once had a recurrence interval of 500 years in New York City now is occurring as frequently as every 25 years (Reed et al. 2015). The second aspect applies to developing cities, where the extreme rapidity of urban expansion, especially in informal settlements of the global South, means that protective infrastructure may not be in place. These two aspects of system state motivate new thinking about cities’ responses to and recovery from disturbance. The four examples above illustrate how the components of the Peters et al. (2011; Fig. 1) framework apply to urban SETS experiencing large disturbances. Aging infrastructure in the global North and lack of infrastructure in the global South illustrate the model of the current system state. Past inequities in housing availability in New Orleans illustrate the effects of legacies. Failure of warning systems and lack of refuges in European and Chicago heat waves are mechanisms leading to impacts, while rebuilding infrastructure or improving warning systems are social/institutional responses. Thus, using the Peters et al. (2011) framework to disaggregate the elements of disturbance may provide a means for organizing the required new thinking.

In the remainder of this section, we apply the Peters et al. (2011) model to four kinds of disturbance: urban land transformation, alteration of urban tree canopy, flooding, and economic recession. Comparing how these disturbances operate in Baltimore and Phoenix reveals...

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**Fig. 4.** System model, drivers, impacts, and responses for the Great Fire of Baltimore, illustrating the social, ecological, and technological aspects of the system that contributed to the fire’s impacts, as well as the largely social drivers and responses, and that led to the city’s recovery.
further subtleties in urban application of the Peters et al. (2011) framework.

**Land conversion**

The disturbance that initiates or extends urbanization in a landscape is a process of land conversion. This process can be disaggregated using the Peters et al. (2011) framework (Fig. 5). The pre-disturbance model of the system may map “greenfields” that can be urbanized. Many factors drive urbanization. For example, urban planning and zoning regulate where building can occur, for what purposes, and at what densities. Economic considerations, such as financing, subsidies, or tax incentives, may affect decision making at scales from government to individual households. Where urbanization occurs may be influenced by characteristics of the larger regional system, such as topography and spatial relationship to other systems and resources. These considerations employ a structural model of a region as distinct, mappable covers.

Urbanization begins with a specific event destroying non-urban land cover and constructing features that constitute urban land. These destructive mechanisms include cessation of the previous management regime, removal of vegetation, excavation, filling, or grading of surfaces, and construction of new buildings and infrastructure. Because urban areas may contain vegetation, construction can also entail planting and maintaining gardens, yards, parklands, street plantings, and so on. Once the system is built, it has changed state from non-urban to urban. The resulting urban land cover is not a disturbance per se; rather, the process of conversion is a disturbance to the non-urban land. The disturbance is itself complex, consisting of many specific actions and physical alterations of the ecosystems being replaced or modified (Fig. 5).

Once an urban system exists, there is necessarily a new model against which any potential disturbance events
must be evaluated. There may be focused disturbances that occur within urban areas, such as removing small bungalows to make way for larger homes, abandoning or demolishing shopping malls that have fallen out of favor, or altering transportation networks to deal with increased traffic. Each of these transformations within the city is a disturbance event with its own drivers that lead to specific mechanisms of change that will result in a particular impact within the urban system. Note that shifting concern from the spread of urbanization into peripheral areas relies on a different model of system state than the focus on fine-scale disturbances within an established urban system.

Two different trajectories of urban transformation that suggest different models of systems structure, both following the Peters et al. (2011) framework, are exemplified by Baltimore and Phoenix. The different models are based on contrasts in their vintage, the rationales of their founding, and their differing connections to regional and global economies. Baltimore City, fueled for 200 years by novel transportation technologies and heavy industry (Olson 1982), reached its population heyday in the 1960s with nearly a million residents, after which it declined by one-third. The suburban counties continue to grow, however, resulting in an increase in metropolitan population and an extension of city/suburban land covers. Drivers of this change are complex and intermingled but include housing and education policy and quality, and racial segregation. Within the established urban landscape, there are individual disturbances, for example, where homes and commercial buildings were vacated and demolished, creating open space. As of 2013, the Baltimore City Department of Housing classified 8% of residential land, or just over 16,000 properties, as abandoned or vacant (BNIA 2015). The abandonment in Baltimore City reflects the historical footprint of racial segregation ordinances, environmentally negative zoning variances, the Federal Home Owners Loan Corporation mortgage redlining, and the exclusionary practices of neighborhood associations (Boone et al. 2010, Lord and Norquist 2010). The model exposing the structural changes of abandonment and demolition in Baltimore City is thus socially and biophysically complex and places the city in a regional context having heterogeneous regulatory, housing market, political power, and economic resources (Grove et al. 2015).

In contrast to Baltimore, Phoenix greatly expanded in both population size and spatial extent during the 20th century, converting desert to agriculture and then agriculture to city/suburban land (Knowles-Yáñez et al. 1999, Jenerette and Wu 2001). This growth was again driven by multiple factors including jobs, housing costs, and a favorable climate (when modulated by the invention of air conditioning), all attractive features to migrants from other parts of the United States and neighboring Mexico. The rapidity of urban expansion after WW II created new housing developments in outlying areas, often leapingfrogging across vacant land (Gober and Burns 2002). Between 1950 and 1980, much of the converted land was farmland (e.g., Lewis et al. 2006). Beginning in the 1990s, the metro area has been expanding directly into desert. Finally, spatial segregation of ethnic minority populations from the founding of Phoenix, via discriminatory housing regulations and lending practices, continued into the 1960s (Bolin et al. 2005). Disproportionate exposure of the marginalized Latino and African American populations in South Phoenix to contaminants and unhealthy living conditions resulted from failure to regulate land uses. Thus, urban land transformations in Phoenix are spatially heterogeneous: a mosaic of open space and managed, developed housing areas, residential landscapes with different soil conditions based on legacies of past land use (agriculture), and mixed-use areas with legacies of past discrimination. Both Phoenix and Baltimore have heterogeneous land use pattern, but the specific drivers, mechanisms, and responses have differed between the two cities.

**Alterations in tree cover**

One of the most visible elements of nature in a city is the urban forest or tree canopy. Because of the measured and assumed benefits that trees provide for urban residents and wildlife, increasing the urban tree canopy is a sustainability goal in many cities. Planting trees has also been a mainstay of community building and urban beautification since the early 1900s (Buckley 2010). Can tree planting or the increase in tree canopy cover, as municipal-scale interventions, be considered a disturbance? Tree planting can be disaggregated using the Peters et al. (2011) framework: Planting has the potential to alter system structure (Fig. 6), it requires mechanisms to break soil and change resource flow in the system, and the ensuing response involves tree growth, expansion of the canopy, and tree death, all of which may involve active, socially mediated management as the system changes.

Applying the framework in contrasting cities such as Baltimore and Phoenix suggests different models, although some factors may be in common. For example, the cities likely share many motivations for an urban tree canopy, including a need to shade and cool the city, enhancing neighborhood identity and aesthetics, providing bird habitat, storing carbon to offset greenhouse gas emissions, and improving air quality. All planting activities change system structure, but the tradeoffs implied by the disturbance will differ among systems having different properties and hence reflecting different models. For example, the City of Baltimore is located in the eastern deciduous forest biome and without human intervention, the climate would support trees. In contrast, Phoenix is located in a desert and without human alteration trees would only be found near surface water. Human management overrides climate, providing the resources for trees to persist in the Phoenix urban landscape (Jenerette et al. 2016).
Once trees are planted and the urban tree canopy expanded, disturbance to the tree or canopy can be inflicted by pest outbreaks or by storms that blow down trees or cause damage to branches. Importantly, shifting attention from the establishment of new urban canopy to understanding the dynamics of established urban tree canopy moves from one kind of model to another. It is not simply trees per se that are the focus. Loss of urban trees through pest or storm damage is also influenced by system characteristics embodied in the new model. For example, storm damage may be highly localized, affecting open-grown trees that are more exposed to the wind than trees grown in clusters, and may affect older trees with fragile limbs. Pests are often species specific, and the species composition and the arrangement of species across the landscape will influence the susceptibility of trees to pest damage. For example, American elm (*Ulmus americana*) trees once graced the streets of many cities and towns in the United States. Dutch elm disease preferentially damages American elm trees. Since its introduction in 1928, the disease has killed more than 75% of American elm trees in the United States.

Finally, deliberate reduction in tree cover, for example, to preserve water resources, or simply to make way for different land covers, also represents a disturbance to established urban tree canopies that can have social ramifications. In the early 1900s, an extensive lateral canal network in South Phoenix featured large, deciduous, riparian trees. Municipal water managers coalesced the water delivery system in the 1950s and 1960s, eliminating most laterals. At the same time, a practice of removing trees to save water for people eliminated all large shade trees from South Phoenix. These decisions disproportionately affected the predominantly minority community of South Phoenix (York et al. 2014), because tree removal occurred in public spaces and these residents lacked tree cover in private spaces. The new state of the system is a hot, dry, and largely unshaded area where people are more exposed to high heat than in other parts of the city where vegetative cover was maintained (Bolin et al. 2013).
Changes in flooding with urbanization

Flooding acts upon coupled social–ecological–technological urban systems, in this case, an urban watershed, and the complex of social and biophysical processes involved in system susceptibility and responses to flooding can be understood by disaggregating the events using the Peters et al. (2011) framework. Here, we explore the impacts of flooding on system structure in the Phoenix, AZ metropolitan area. In this case, our system model includes both built and green landscape structure and social structure, including the governance of stormwater and flooding systems, as well as social and demographic factors. Flooding disturbances are affected by the interaction between precipitation as a driver and the properties of the built environment—imperviousness, stormwater and flood control infrastructure, and the location of property (Fig. 7). In early September 1970, severe flooding occurred across Arizona. In Scottsdale, AZ, four inches of rain fell over 3 days, more than half the annual average rainfall for the region. Runoff, exacerbated by impervious surfaces, overwhelmed the capacity of drainage infrastructure. To make matters worse, the pattern of development at the time meant that many homes were in the floodplain. As a result, the impact of the flooding included the evacuation of 250 homes in Scottsdale, erosion of sediments, and the destruction of roads, bridges, landscaped vegetation, and homes (Roeske et al. 1978).

The system response to the flooding was shaped by these extraordinary impacts as well as by social drivers and processes that included ongoing social debates about flood management begun as a result of earlier floods. As early as the 1960s, the Army Corps of Engineers had designed a concrete flood control channel for the city of Scottsdale to deal with recurring flooding, in keeping with the prevailing management paradigms. However, an active Scottsdale citizenry was opposed to a concrete channel and argued for a more innovative design—a greenbelt—that was incorporated into the city plan in 1967. This laid the groundwork for the response to the 1970 flood: A bond issue passed in 1973 to fund...
the creation of a greenbelt that would serve as flood control as well as a recreational amenity. Following the passing of the bond measure in 1973, the system continued its recovery from the flooding event: Construction began on the greenbelt, accompanied by the removal of houses from the floodplain. In 1984, construction was completed, and the new system state was dramatically different than before, with a more pervious floodplain and a chain of lakes and streams that slowed floodwaters (Roach et al. 2008). This change in system state then had implications for flood risk into the future, likely reducing damages that would have occurred without it. In the case of urban flooding, a physical disturbance interacted with the built environment to determine the impact of the disturbance, but long-term changes due to the disturbance were a consequence of the social and technological response.

Economic disruption

Phoenix provides our final example, where we apply the Peters et al. (2011) framework to consider how a large-scale economic disturbance can alter the social and biophysical structure of urban ecosystems (Fig. 8). The 2008 recession had profound impacts on urban residential landscapes in the Phoenix metropolitan area. The residential landscape system encompasses biophysical structures of soils, vegetation, irrigation infrastructure, as well as social components of neighborhood structure, social norms, and regulations regarding landscape management and design (Cook et al. 2012). Key interactions in this system include landscape management by weeding, fertilization, or watering, and the delivery of ecosystem services. Far from being closed systems, the structure and function of residential landscapes is influenced by cross-scale interactions such as norms, rules designed by homeowners associations (HOAs), municipal ordinances, and at the largest scale, patterns of urban development. In 2007, the U.S. housing market crashed, leading to a recession. Economic policies and regulations, market processes, and social norms all led to the housing bubble and subsequent crash (i.e., the disturbance mechanisms). The mechanisms of the disturbance were primarily social: As people were unable to afford mortgage...

**Fig. 8.** Social disturbance leading to ecological reorganization in response to the Great Recession in Phoenix, Arizona.
payments on their homes, foreclosures became frequent, and construction of new houses ceased and some existing new houses were abandoned. In essence, the process of urbanization was halted. Other social processes also amplified this disturbance, through the effects of foreclosure on the price of nearby homes and the loss of income for HOAs. Furthermore, willingness to pay for environmental amenities such as landscape management likely decreased, as has been reported elsewhere (Cho et al. 2011, Minn et al. 2015). A major impact of this disturbance in Phoenix was the loss of a key interaction in residential landscape systems: With foreclosures came a loss of landscape management and associated planting, fertilization, and irrigation—all of which are essential to support the types of residential landscapes found in this aridland city. Thus as the system recovered and reorganized from the disturbance, there were shifts in the composition of vegetation, including an increase in annual species (Ripplinger et al. 2016) and declines in NDVI, a relative measure of vegetation health and density (Minn et al. 2015), as desert conditions prevailed. These shifts were driven by ecological processes, including succession, dispersal, competition, and resource dynamics. In this case, a social disturbance removed a key interaction between humans and the biophysical structure of the system, and cascading ecological processes led to a shift in system state.

Conclusion

The general concept of disturbance as a discrete event with sudden onset that disrupts the structure of a system, combined with the Peters et al. (2011) framework for operationalizing the concept of disturbance, provides a useful new synthesis for understanding how disturbance operates in social–ecological systems, including urban SETS. The term “disturbance” was chosen by Pickett and White (1985), in part, to be provocative in the context of the predominant equilibrium ecology of the late 20th century. Because it is a loaded term, care must be taken to unpack its hidden assumptions and facilitate rigorous understanding of the dynamics of ecological systems. This is especially true for urban systems, where biophysical and social drivers, mechanisms, and system components jointly contribute to SETS dynamics.

While various potential disturbances may constantly exist in urban landscapes, neither urban landscapes nor all activities occurring within them are always, by definition, disturbances. Our understanding of urban disturbance will not progress until we excise this unhelpful generalization from our thinking.

Most critically, disturbance can only be defined after a system model has been specified, since the same activity may be a disturbance at one space or time scale, but not at another. It is exactly this problem of model specification that has conceptually hindered urban disturbance ecology. In fact, model specification is probably one of the biggest hurdles to advancing the application of disturbance theory to empirical research in urban SETS. Models of urban systems that support understanding the identity, effects, and recovery from disturbance are perhaps more complex than the models for most non-urban systems because of the need to address (1) the role of cultural values, political power, and social equity; (2) the mix of SETS components and interactions, and (3) the persistent social, physical, and technological or infrastructural legacies so common in cities, suburbs, and their exurban fringes. Disturbance definition is closely related to system scale, a finding that certainly applies in non-urban systems, but is particularly evident in urban SETS.

A final critical aspect of disturbance in urban SETS is the important role of cascades and interactions among events. Disturbance in one aspect of the system—economic policy—can lead to a disturbance in another aspect—management and care of urban trees. Disturbance drivers may interact. In our case studies, we found that social processes can have cascading effects on biophysical structure and function and vice versa and that the social responses to disturbances are a critical aspect of understanding how urban systems change over time (e.g., through changes in infrastructure or regulations). Furthermore, the implications of including social drivers, responders, mechanisms, and disturbance types go beyond urban systems to all social–ecological systems. For example, fire regimes in the western United States, often considered as an ecological disturbance, are strongly affected by human decisions about fire control and forest management. Thus, our adaptation of the Peters et al. (2011) framework echoes the recognition of humans as components of all ecosystems, whether in conserved, working, or built landscapes.

This framework, and the clarity that it brings to considerations of disturbance and resilience in urban SETS—especially with regard to the system model, drivers, mechanisms, impacts, and responses—will be of use to urban practitioners. Whether or not they use the term, many urban planners and managers are concerned about disturbances that are increasing both in frequency and in magnitude in their cities. The ubiquitous use of the term “resilience” is related to this increase in extreme events, in the face of which cities must cope, adapt, or fail. Given that resilience characterizes how a system is able to withstand “shocks” and “perturbations”—disturbances, in essence—this framework can bring clarity to decision makers’ strategies to enhance resilience of their cities, city infrastructure, social systems and institutions, and populations.

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