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From feedbacks to coproduction: toward an integrated conceptual framework for urban ecosystems

Anne Rademacher[1] · Mary L. Cadenasso[2] · Steward T. A. Pickett[3]

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Abstract

Research in urban ecology depends on frameworks that meaningfully integrate our understanding of biophysical and social change. Although the coupled nature of urban ecosystems is widely accepted, the core mechanisms we use to integrate the social and biophysical aspects of urban ecosystems – their social-ecological feedbacks – are poorly understood. This paper considers how feedbacks are used to conceptualize social-ecological change, noting their utility and their limitations. In so doing, we suggest that *coproduction* provides a meaningful alternative to feedbacks, one that captures not only the structure-function relationships usually assumed in studies of biophysical landscape change, but also the structure-agency relationships that facilitate our most comprehensive understanding of social change. By addressing both the stepwise forms of transformation that a feedback approach captures and the simultaneous forms of transformation captured by a coproduction approach, a more comprehensive assessment of the ways that social and ecological change take place is afforded. We contend that thinking in terms of coproduction is essential for moving beyond the *interdisciplinary* approach that usually guides urban ecology models, toward a more integrated, *trans-disciplinary* approach.

Keywords Coproduction · Social-ecological systems · Framework · Transdisciplinary · Urban ecology · Feedback

Introduction

In recent decades, a wide range of scholarly interests and disciplinary subfields have galvanized around urban ecology. Cities, and more broadly urban contexts,[1] present researchers with settings in which clearly separating "social" and "biophysical" spheres is virtually impossible, and nearly always incomplete. Work in cities has thus compelled clearer

✉ Anne Rademacher
Ar131@nyu.edu

Mary L. Cadenasso
MLCadenasso@ucdavis.edu

Steward T. A. Pickett
picketts@caryinstitute.org

1 Departments of Environmental Studies and Anthropology, New York University, 285 Mercer Street 906, New York, NY 10003, USA

2 Department of Plant Sciences, University of California, One Shields Ave. Davis CA, Davis 95616, USA

3 Cary Institute of Ecosystem Studies, Box AB, Millbrook, NY 12545, USA

[1] A distinction between the term *urban* and *city* is drawn by many scholars, and in this paper, to signal Lefebvre's (1970) assertion, that, by tracing the capitalist flows that bind the spatial configurations we tend to refer to as "city" and "countryside," we are poised to recognize a completely urban world. That is to say, the consequential flows between cities and their surrounding territories – be they of materials, information, people, power relations, and so on – establish forms of interconnection that are most meaningfully regarded as constituting the urban form. Thus, urban systems include cities but are never confined to them, or defined by their boundaries. In the social sciences, geographers have been particularly prolific in generating such urban mappings (e.g., Harvey 1973) and have recently advanced highly influential propositions such as Brenner's (2014) suggestion of *planetary urbanism*. This idea takes issue with definitions of the urban and urbanization that use the city and its demographic contours as a primary basis for analysis. Instead, planetary urbanism emphasizes the almost infinite connectivity between concentrated city zones and their hinterlands. See also the formulation of "ecologies of urbanism" in Rademacher and Sivaramakrishnan 2017 and Rademacher and Sivaramakrishnan 2013.

scholarly acknowledgement of the interconnected nature of social and biophysical change. Although urban ecology research spans a vast and diverse disciplinary continuum, what unifies its scholars is a shared desire to empirically capture, and more fully understand, the intertwined nature of social and environmental change.

Yet it has long been the case that while multiple disciplines claim "urban ecology" as a focal arena, each tends to apply very different theoretical and methodological tools to urban ecological research. Although we use shared analytical terms, such as resilience, sustainability, and even "urban" itself, these often signal very different, discipline-specific meanings and assumptions (Walker 2011; Adger 2000). For example, many scholars use the term "urban" in a way that is interchangable with "the city." In contrast, our use of the term in this paper reflects a different meaning, first suggested in Henri Lefebvre's formulation of an "urban revolution" (Lefebvre 1970). This position, exemplified in Neil Brenner's recent (2013) work, and Rademacher and Sivaramakirshnan's "ecologies of urbanism" (2013, 2017), emphasizes the almost infinite connectivity between concentrated city areas and their hinterlands. In this paper, we use "urban" in this sense of interconnection: we presume that all landscapes are coproduced, and that although coproduction may be more apparent in cities, it is by no means restricted to city landscapes (see also Diener et al. 2001; Harvey 2010).

Another recent example of shared terminology but divergent assumptions is the widespread use of the term "resilience." The ecological sciences have witnessed a radical shift in its definition and use (Holling 1996; Carpenter et al. 2001), commonly revealed by the use of modifiers: engineering resilience vs. ecological resilience (e.g. Pickett et al. 2013, Wu and Wu 2013). Engineering resilience refers to the perspective that systems have one stable state, so the resilience of the system is a measure of how fast it returns to that state following a disturbance or disruption. By contrast, ecological resilience recognizes that, more commonly, systems have multiple stable states. Here, resilience is the capacity of a system to adjust and absorb the changes brought about by a disturbance or disruption without changing the fundamental structure or function of the system, or without moving it to a different state. Social researchers also tend to use resilience in distinctive ways (Adger 2000; Gotham and Campanella 2010; Walker and Cooper 2011; Levine 2014). When some social researchers analyze "community resilience," for instance, they look at factors that influence the capacity of a given social group to withstand specific types of disruption or disaster. In this context, certain forms of social reorganization or transformation may be regarded as precisely the opposite of resilience.

Our aim in this paper is not to review all uses of these terms, nor is it to provide a full history of their changing uses in the social or ecological sciences. Instead, we point to their many meanings in order to underline the potential for major interdisciplinary misunderstandings and errors. Despite differences in the use of shared terminology, multiple attempts to produce more integrated urban ecology frameworks have helped to unite scholars over common concerns and mutually legible research operations. Our vocabulary underscores a unity of purpose, then, but can sometimes create a false sense of interdisciplinary continuity. Divergent meanings can also lead to highly consequential errors (Pickett and Cadenasso 2002; Dove 2001; Pickett et al. 2007), making the interdisciplinary work essential to fully understanding urban environments especially challenging.

In this paper, we note that specific shortcomings remain. Among these is the fact that, although few urban ecology scholars would dispute *whether* social and biophysical change are interconnected, our tools for understanding *how* – theoretically and methodologically – remain incomplete. In other words, if we begin from the assumption that urban systems are hybrid, and as such, coproduced, then the challenge we face is to answer the question of how hybrid systems are coproduced. To date, the most common way to represent the connected mechanisms of social and biophysical change is social-ecological feedback – usually demonstrated by the arrows or lines that link separate biophysical and social categories in most urban ecology frameworks and models.

We distinguish carefully between the terms framework, model template, and model in this paper, in order to emphasize the important theoretical and operational differences between them. While a framework is a dynamic and always incomplete list of important factors related to a given social and ecological condition, a model template demonstrates how the collection of factors relevant to a given problem are potentially linked to each other.[2] A model, in turn, derives from the model template, and, because it is context-specific, the model identifies particular factors and relationships to be tested. Consequently, numerous models could be derived from one model template. The distinction between framework, model template, and model is critical in this paper, particularly because it allows a distinction between a never-complete formulation of the processes involved in social-ecological change, and their case- and context-specific applications (Cadenasso et al. 2003; Pickett et al. 2007).

To follow, we review progress in theorizing social-ecological feedbacks and address a specific shortcoming in the resulting frameworks and model templates. Namely,

[2] By "Model template," we mean to refer to a representation of the components, flows, or interactions that can exist within a system. A model template is used to develop models of specific systems, places, or circumstances. A single template, then, can beget many potential models.

social-ecological feedbacks capture stepwise forms of social-ecological change, but they do not adequately capture simultaneous, mutually produced forms of social-ecological change. We suggest that the concept of *coproduction* provides a potentially corrective and meaningful alternative. Our effort to advance the idea and empirical potential of coproduction acknowledges from the outset that, as is the case with many terms shared across the continuum of urban ecology research, coproduction signals different meanings in different disciplinary arenas.

We conclude that the theoretical differences that distinguish social-ecological feedbacks from co-production can advance the study of urban ecosystems beyond the contemporary scenario of conceptualizing coupled social and biophysical systems. We show that coproduction suggests a more integrated, social-ecological hybrid theoretical and methodological approach. Despite increasing calls for transdisciplinary work in urban ecology, much of the theoretical and operational groundwork remains. Our aim is to strengthen our capacity to undertake transdisciplinary urban ecology work by showing that coproduction allows a more hybrid social-ecological approach.

Current uses of coproduction

Coproduction is used in a variety of ways across scientific and social studies in urban ecology. In ecology, it usually implies that research agendas – that is, questions, approaches, and interpretations – are generated in active dialogue between researchers and communities or decision makers (Lemos and Morehouse 2005; Childers et al. 2015). In this sense, it is the *research agenda* that is produced in partnerships that aim to combine a broadly construed community of "stakeholders" (citizens, community groups, NGOs, government agency officials, elected representatives) with the researchers and scientists who seek to answer urban ecology questions.

Among social researchers, coproduction sometimes signals the analytical tradition of Science and Technology Studies (STS), where it is used to emphasize the social and institutional dynamics of scientific knowledge production (Callon 1995, 2009; Gieryn 1995; Jasanoff 2003, 2004a, 2004b). In this sense, coproduction is used to emphasize knowledge production itself, and the conditions in which science is itself made, conveyed, and used. Scientific knowledge is, in this usage, analyzed as a social product that cannot be isolated from the political dynamics and social power relations that shape the conditions within which it is made. As the environmental historian and theorist Jens Lachmund has written, this sense of coproduction emphasizes "the simultaneous constitution of science (including its orderings of nature) and the social worlds in which it is embedded" (Lachmund 2013:5). Similarly, Muñoz-Erickson et al. (2017) use coproduction to underline the linked ways that scientists, practitioners, and policymakers identify problems, formulate solutions, and operationalize those solutions.

Another arena in which coproduction is used among social researchers is in their engagement with ecosystem services. Fisher and Eastwood (2016), for example, recently argued that the very idea of ecosystem services must be coproduced with social groups; since ecosystem benefits depend on their designation as such – by humans – ecosystem services cannot exist independently from social groups. In other words, it is human value designation, via sociocultural processes, that determines what constitutes an ecosystem benefit.

The concept as we will outline it below is distinct from these other uses: in this paper, coproduction provides an analytical tool for understanding *how* mutually generated social-ecological change takes place, not a process for determining what research agenda will most effectively address a given environmental problem, or a term that focuses solely on the social production and circulation of scientific knowledge. In this paper, we define coproduction as mutually generated social-ecological change, and distinguish it from the stepwise, one-change-begets-another form of change that is implied by a social-ecological feedback approach.

How are social and biophysical change interconnected? The role of feedback

Across the biophysical sciences and social sciences, one finds longstanding efforts to understand how human and nonhuman change are interlinked. In the sciences, concepts and ideas once foundational to ecology have been revisited, revised, and reworked (Pickett and Grove 2009; Kingsland 2005). In recent decades, the idea of interconnected natural and social change has generally been conveyed through systems formulations, but systems thinking presents both an advantage and, at times, an obstacle. On one hand, a systems approach enables a shared capacity to identify, theoretically represent, and methodologically operationalize our study of the complex domains of social and biophysical change. On the other, the systems frameworks on which our various model templates are based may differ considerably, leading to important misunderstandings, and even unintended uses of or assumptions about, urban ecology models.

Many of these differences relate to the histories of the specific disciplines that urban ecology seeks to analytically unite. For example, the relationship between environmental and social change was a core focus of early work in anthropology and sociology, but the way it was studied and debated has led to specific assumptions about systems thinking in general.

An early example of social scientific engagement with social-ecological relationships was Durkheim's *Primitive Classification*, which famously argued that the relationship between nature ("the macrocosm") and culture ("the microcosm") formed the foundation of human cognition and social organization (Orr et al. 2015). Later, the anthropologist Roy Rappaport analyzed this relation in terms of what he called, "ecological functionalism," an assertion that, despite widespread critique, foregrounded the question of whether and when social processes (in Rappaport's case, specific ritual patterns) were connected to particular biophysical conditions (in his case, soil fertility, protein distribution, and human population regulation) (Rappaport 1968; Vayda and McKay 1975; Kottak 1999).

While scientific ecologists refined and reworked the core concepts in their ecological systems formulations, environmental social sciences debated whether systems thinking reinforced ideas of ecological functionalism or structural determinism. In general, the need to reserve a place for conceptualizing human agency in theories of social change led many in the social sciences to avoid systems formulations altogether. The place, and relative power, of human agency in social-ecological change sustains vigorous debates that continue to shape contemporary work in the environmental social sciences. This is particularly visible as scholars debate the suggestion of "agency for nature".[3]

Orr et al.'s (2015) review of systems formulations in environmental anthropology, for example, argues that "systems ecology provides tools to investigate the consequences of decisions, but has nothing to say about decision-making processes." (Orr et al. 2015:157). That is to say, systems ecology in general and urban ecology more specifically seem to Orr and colleagues to provide precious little place for human agency in conceptualizing the 'social action' aspect of urban ecology models. If urban ecology in the natural sciences takes keen interest in biophysical structure-function relationships, urban ecology in the social sciences considers social structure, social functions, *and* human agency in social relationships.

We contend that divergent, and partial, conceptualizations of how social-ecological change takes place, and how to best capture it, are at the root of the shortcomings of social-ecological feedbacks as a concept. The arrows that usually mark points of interconnection, or the possibility of a relationship, in our frameworks, model templates, and models, are often interpreted in terms of structural causality in the social sciences. Furthermore, they have yet to fully capture or convey the complexity of the interconnections they signal.

To clearly distinguish our approach from any suggestion of deterministic structure-function assumptions in human social systems, we underline here that contemporary systems ecology fully rejects historical ideas of biophysical systems as closed, tending toward balance or homeostasis, or demonstrative of fixed causes and assured effects. All the systems we invoke in this paper are consistent with current ideas of ecological (human and biophysical) systems, which are assumed to have the following characteristics (Simberloff 2014; Egerton 1973; Pickett et al. 1992; Pickett et al. 2007):

- They are open
- Their regulation can include external influences
- Their dynamics are not necessarily deterministic
- There isn't necessarily a single stable point
- Disturbance can be a part of systems, and is often expected
- Humans are components of ecological systems

While they may be at an impasse as to how, urban ecologists in both the social and natural sciences agree that biophysical and social change are interconnected. Yet the mechanism we use to signal that connection – the arrow or the line – is at present insufficient.

Social-ecological feedbacks are a specific type of connection in which change in one aspect of a given system generates change in another. This, in turn, feeds back to the first. This reciprocal relationship can exist between materials, information, energy, and a range of relevant social processes. The current use of the term in urban ecology tends toward two limitations. First, the connections between social and biophysical processes are often mistaken for designations of stepwise causality – that is, that a given biophysical change begets a particular social change or vice versa. One challenge this presents is whether and how we might more fully and accurately capture the dynamism of human agency in a way that does not rely on stepwise, structurally-determined change. Related to this, contemporary uses of social-ecological feedback beget the idea of *coupled* human-natural systems, a mode of thinking that tends to reify distinctive domains that are clearly designated as social versus biophysical systems, even as urban ecologists such as Redman et al. (2004) argue that the two domains exist in an integrated relationship that can imply mutual production.[4]

[3] In Rademacher 2015, the author notes that, "whether described as "agency for nature," as "multispecies ethnography" (Kirksey and Helmreich 2010; Ogden et al. 2013), or through a host of other terms, sensitivity to the sometimes profound role of nonhuman nature in structuring (Abrams 1982)—albeit with tremendous dynamism and unpredictability—the human individual and collective capacity for agentive action has compelled new analyses of power relations, new historiographies, and a particularly complex idea of the human agent. Multispecies ethnographies, together with the field of science and technology studies and its use of actor-network theory (Callon 1986; Latour 1988, 1993a, 1993b; Latour and Woolgar 1986), flourish among a host of scholarly movements and "posthumanities" (Wolfe 2009). But the work of assembling robust ethnographic and clearly historicized portraits of urban socionatural transformation, and of reaching beyond the laboratory and other conventional domains in which we analytically locate urban scientific knowledge production and ideas of urban nature, is notably scarce in these otherwise vibrant fields" (Rademacher 2015:143).

[4] Redman et al. 2004, whose figure that appears in this paper (Fig. 6), calls in part for a co-production approach. Although they do not use the term itself, they call for "integration" in social-ecological systems that resonates with our use of coproduction in this paper.

It is useful here to return to the specific terms that accompany various uses of systems theory in urban ecology, shown as Table 1. Traditionally, scholars from the social and ecological sciences came together in a multidisciplinary approach. The present norm, however, is an interdisciplinary approach to human and natural systems that begets a coupled understanding of urban ecological change. Our aim is to move beyond this, toward a transdisciplinary approach that draws on an assumption of mutually produced human and natural change. This latter mode of understanding hybrid social and biophysical processes, we contend, more adequately captures how biophysical and social change take place.

Beyond feedbacks: Toward coproduction

In order to explore the strengths and limitations of social-ecological feedbacks, it is instructive to begin with a prominent framework for understanding how social and biophysical change are interconnected. The Human Ecosystem framework, formally proposed by Machlis et al. 1997 but conceptualized as early as the late 1970s, has been widely adopted, refined, and applied to active urban ecology research (Machlis et al. 1997; Burch 1988; Grove and Burch 1997).[5] Although first proposed as a model, the Human Ecosystem framework has since become widely used and accepted as a framework.

In Fig. 1, an early rendering proposed interconnected human social and biophysical processes in two domains: a "human social system" and "critical resources." The latter were divided into three subcomponents: natural resources, socioeconomic resources, and cultural resources. A great deal of rethinking and refinement has led to multiple revisions and elaborations of this framework, but for present purposes we note the importance of the *signals of interlinkage*: the arrows between domains indicate that while they may be studied, and even understood, separately, the processes identified inside the framework's various boxes *are related and may be relational*. Change within them is signaled by connective arrows, but a clear sense of how changes take place, that is, the precise form of change that the arrows represent, is left for further conceptualization and testing.

Table 1 Types of systems and appropriate study approaches

System type	Approach
Co-produced (hybrid)	Transdisciplinary
Coupled (e.g. human-natural)	Interdisciplinary
Ecological (biotic - physical)	Disciplinary
Social	

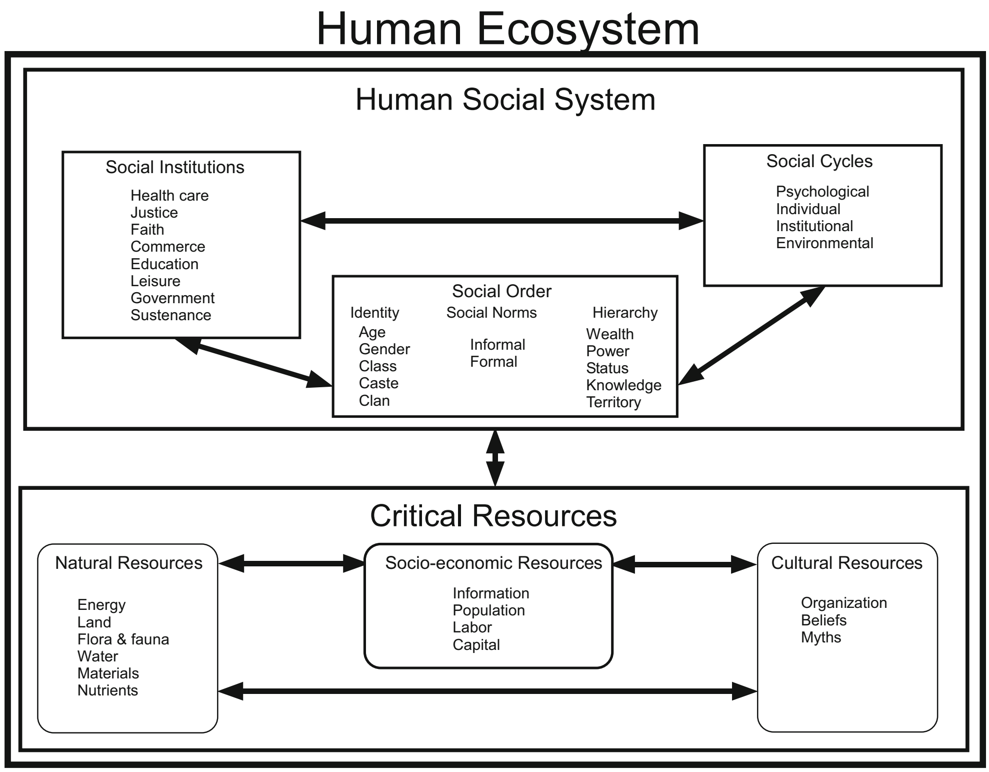
Invoking this early iteration of the Human Ecosystem framework allows us to underline that, although many different versions and histories of urban ecosystem templates exist, all hold a common, longstanding commitment to systems as both a useful way of thinking about interconnected biophysical and social change, and as a useful way to consider the mechanisms of interconnection itself (e.g. Redman et al. 2004). Likewise, all iterations of the framework maintain a commitment to identifying the meaningful and most relevant components of the system under consideration[6] *and* their interconnections, through arrows, lines, or some other connective signifier. Although the arrows are the least graphically visible part of the diagram, the actions, interactions, and agencies they imply are as significant in the conceptualization as the nouns that identify the parts of the framework. The arrows stand for verbs – such as replaces, supplies, competes with, transforms, and so on – in the human ecosystem framework. Particular verbs are specified when researchers construct an operational model based on the template of the human ecosystem.

Yet the arrows also mark an important site of potential misunderstanding between urban ecologists positioned in the natural sciences, and those positioned in the social sciences. In the latter, arrows are often mistaken for signals of causality or determined outcomes, a result, in part, of the history of social science engagement with social-ecological change discussed above. The frameworks themselves, therefore, might be easily misinterpreted as modes of capturing some forms of social-ecological change, but not others.

[5] In the biophysical sciences, we note the generative work of researchers associated with the two urban sites among the US National Science Foundation's Long Term Ecosystem Research (LTER) initiatives. These urban ecology research centers have long forged new ground in scientific theory and research on urban ecosystems and have made significant contributions to the research tools available to scientists, social researchers, and design practitioners. An exemplary recent volume that captures the interdisciplinary accomplishments of this work, and its innovative models of urban ecosystems, is Pickett, Cadenasso, and McGrath's (2013) *Resilience in Ecology and Urban Design: Linking Theory and Practice for Sustainable Cities*, but the wealth of particular and integrative studies produced in the Phoenix and Baltimore LTER's, as well as other ecosystem-science grounded urban ecology research consortia in North America and beyond, is vast indeed. For our purposes, it is critical to notice longstanding efforts among ecosystem scientists to capture social dynamics in their conceptual and research models, and to join studies of urban biophysical processes and change with sophisticated studies of social context and processes.

[6] It is important here to emphasize that systems may operate at multiple levels. At whatever level, systems are integrated and interactive entities. Material systems are parts of nested hierarchies. A model template will identify specific mechanisms and causes (the interactions, actions, influences, and constraints that result in a state change or a change of systems).

Fig. 1 Modified from Machlis et al. (1997)



Another major difference in the theoretical and operational assumptions urban ecologists positioned in various disciplinary spheres tend to make relates to the items included in the framework itself. We underscore here that a framework is never fixed, finished, or assumed to be a fully exhaustive list, but note that many urban ecologists positioned in the social sciences might regard it as such. Social scientists who work primarily with qualitative data and undertake participant-observation research with human communities, for instance, tend to restrain from positivist or hypothesis-driven inquiry, preferring instead to employ iterative or interpretive approaches. This often leads to restraint when identifying relevant social processes a priori, in part because of a methodological commitment to the iterative discovery of the most important aspects of a given socio-environmental problem. In this context, the very composition of a prior list carries with it the risk of implying that it is somehow total or complete.

Yet note that this second assumption is grounded in the idea that ecosystems are fixed, closed, and totalizing entities, which contradicts our description of contemporary systems thinking above. If we accept that all frameworks are necessarily provisional rather than whole, complete, and constant representations of urban ecology processes, then it is always theoretically possible to add, subtract, and otherwise revise the factors that researchers regard as relevant and active in a given system over time. For example, expansions of the human ecosystem framework by biophysical ecologists add richness to the "natural resources" component in the original. Cadenasso et al. (2006) and Pickett et al. (2011) add such things as dimensions of biodiversity (identity, source, evolution, and guilds), and features of spatial heterogeneity (patch mosaic, configuration, and disturbance), while others complement the detail originally included by the social scientists (Machlis et al. 1997). Dynamism, both social and biophysical, thus characterizes all urban ecology situations.

In Fig. 2, a social-ecological feedback model template presented by Collins et al. (2011) exemplifies one state of the art attempt to theorize and represent social-ecological feedbacks, and their relationship to a coupled social-ecological systems approach to urban ecosystems. The right section of the model presents the structure - function relationships that characterize biophysical ecology, while the left represents social-cultural-economic processes characteristic of the human social arena. In this model template, the connection between them is mediated further by the ideas of ecosystem services and events. These two connection points recognize that the structure-function relationships of biophysical systems provide benefits or services to humans, and that the human social arena influences events that impact the biophysical system. Examples could include climate change, land modification, the frequency of fires, and many others. This type of feedback model template uses social-ecological feedbacks to reinforce two distinct, separate systems: one is social; the other is biophysical. We note that

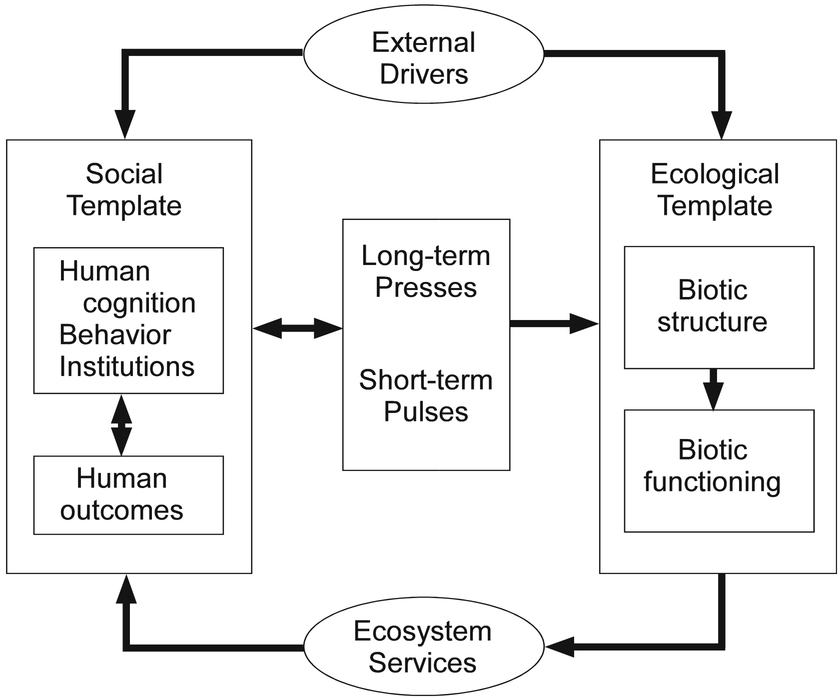


Fig. 2 Based on Collins et al. (2011)

this model results from a series of interdisciplinary workshops that involved social scientists and biophysical scientists, convened to help expand the Long-Term Ecological Research Network of sites[7] so that they more fully consider social processes.

The feedback model template in Fig. 2 captures the form of interconnected, social and biophysical change (Fig. 3a). In the simplest terms, the feedbacks in the top portion of Fig. 3 illustrate a "coupled" mode of conceptualizing social-ecological change: changes in the biophysical sphere generate changes in the social sphere, and this in turn feeds back to the biophysical sphere. This is "coupled" in the sense that the mechanism through which change is understood is theorized according to distinct social and biophysical spheres. Here, social-ecological feedbacks as they are presently conceptualized both reproduce the idea of distinctive and distinguishable social and biophysical domains, and compel us to expect change to take place in a stepwise fashion that can be easily mistaken for a structure-function, or even a direct causal, relationship.

Yet as we noted previously, the presence of arrows in Figs. 1, 2 and 3a do not suggest pre-determined causality. They do, however, indicate feedback relationships that reinforce a *coupled* understanding of the system.

In some cases, it may be entirely appropriate and accurate to understand social and biophysical change in a stepwise, and even demonstrably causal, pattern. However, a great deal of urban ecological change is mutually produced. That mutual production prevents any meaningful step-wise delineation of effects, and resembles more closely Fig. 3b, labeled *coproduced*. In Lachmund's (2013) analysis of areas of

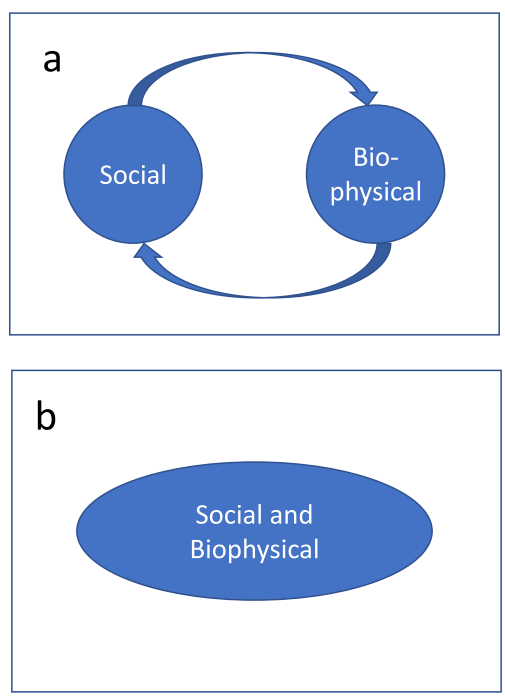


Fig. 3 The contrast between feedback (**a**) and coproduced (**b**) models of social-biophysical systems

[7] Since 1980, the United States National Science Foundation has supported long term ecosystem research at several sites in North America (http://www.lternet.edu/). Two of these are expressly urban sites: the Baltimore Ecosystem Study (http://www.lternet.edu/sites/bes) and Central Arizona-Phoenix Long Term Ecosystem Study (http://caplter.asu.edu/). Both urban LTER sites maintain extensive online libraries of data and analyses.

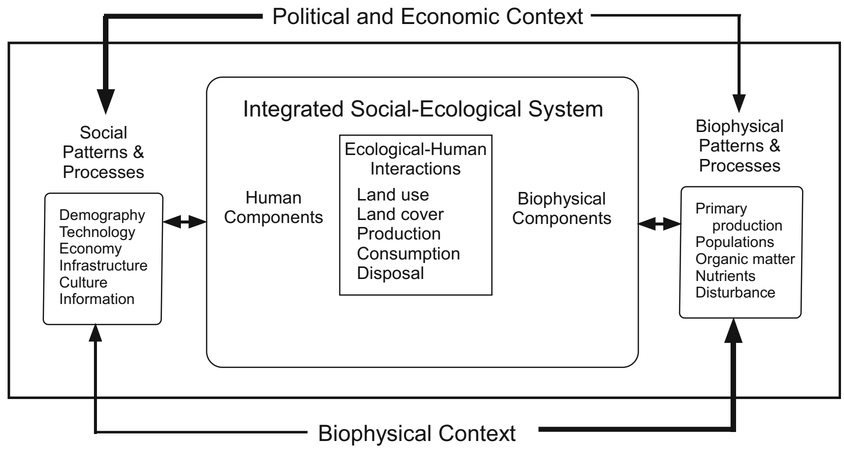


Fig. 4 Based on Redman et al. (2004)

volunteer vegetation in West Berlin, for instance, the author notes that on one hand, such vegetation was a clear result of the unassisted establishment and growth of plants on rubble and cleared sites after World War II. On the other hand, their creation as areas of scientific focus, and later conservation action, were clearly social and political outcomes. Lachmund thus views this as coproduced, showing that *social and natural processes were intertwined rather than sequential or necessarily causal*. Thus, while in some cases change in a system is best understood by invoking coupled dynamics, in others the dynamics of change may be coproduced.

Below, Fig. 4 shows an early effort to represent integrated social and biophysical change in urban ecosystems, and presents an example in which *both* coupled and coproduced change may be present. Here, the form of change that the arrows represent may be coupled, but the components within the central oval suggest coproduction within the integrated system.

The consequences of coproduction

The implications of adopting a coproduction approach are potentially far-reaching. One way to appreciate this is to consider the consequences of coproduction by examining two model templates focused on heterogeneity. We turn to heterogeneity in part because of its place as a key concept for urban ecologists who span the social science-biophysical science continuum. Indeed, most urban ecologists would agree to the definition of the city itself as a "spatially heterogeneous and temporally dynamic mosaic" (Pickett et al. 2017:2) and recognize that social and biophysical heterogeneity can assume many forms. While biological ecologists may evaluate heterogeneity by assessing the differential distribution of vegetation types or species richness in a given urban area, for example, social scientists may look at heterogeneity in that same area by noting differential patterns of income, rates of home ownership, or access to parks and other green, vegetated

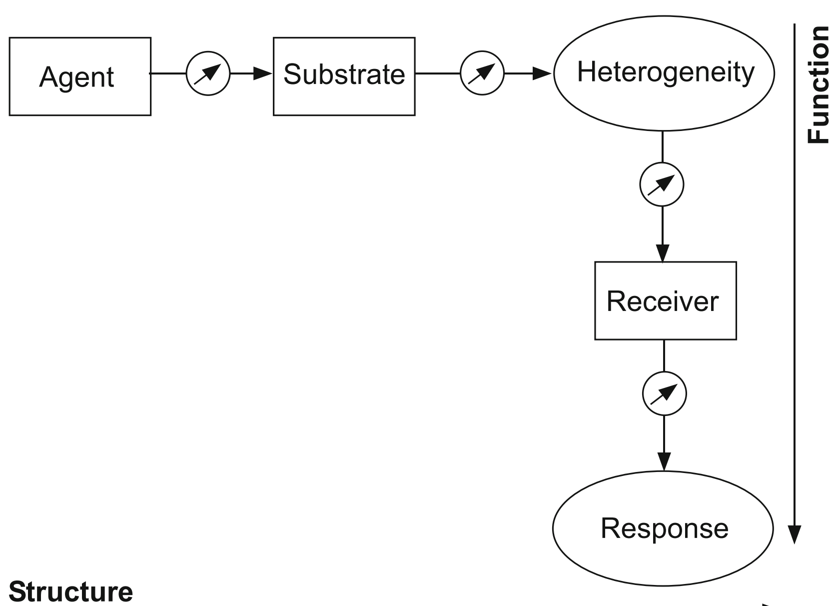


Fig. 5 The transformation of heterogeneity in social-ecological systems. Heterogeneity at some starting time, t1, is converted to a new pattern of heterogeneity at a later time, t2, due to the joint action of biophysical processes and the perceptions and interventions of humans and their institutions. This basic template of coproduction can be applied to any social or biophysical heterogeneity in social-ecological systems. Based on concepts in Pickett et al. 2017

spaces. In important ways, shared attention to heterogeneity facilitates integrative, long term research that can be truly interdisciplinary, and, as we explain below, can provide a platform for investigating both coupled and coproduced forms of social-ecological change (Pickett et al. 2017; Dow 2000; Pickett and Cadenasso 2008; McGrath and Shane 2012; Qureshi et al. 2014; Grove et al. 2015).

To illustrate how, we revisit two model templates of heterogeneity. First, consider Fig. 5, a model template originally developed for understanding the creation of spatial heterogeneity in savanna systems. This model template captures the feedback idea, and therefore depicts a coupled, stepwise sequence of social-ecological change. Here, the structure of the system is created by the set of interactions across the horizontal axis, while system function is displayed in the vertical axis. An action is introduced by an agent[8] – an organism, for example, or a physical force such as wind – acting on a substrate (Sub) – such as soil or an urban form – to create heterogeneity. In order for the heterogeneity to be functional, some entity must be sensitive to it, and react. Circles with small arrows, or "dials," indicate that such interactions have different, condition-dependent intensities.

Though this model template was initially developed to organize thinking about the causes and consequences of heterogeneity in savanna systems, it should be equally applicable in urban systems. For example, the model template might be applied by focusing on the heterogeneity created in some biological aspect of an urban ecosystem, and the "functional" response of some social structures or processes. The social heterogeneity might in turn affect other spatial mosaics in the city, including the initially considered biological one. Such a mechanism would appear as a ratchet with a click of the biota to a new state of heterogeneity, creating the potential for a social mosaic to respond. For example, trees are usually heterogeneously distributed throughout a given city, and areas with low tree canopy cover are hotter than those with higher tree canopy cover. Residents in hotter neighborhoods may respond by employing heat intervention strategies like using air conditioning or advocating for city-sponsored cool down centers. They may also respond by changing, or seeking to change, the biophysical structure of the neighborhood through tree planting efforts that are intended to reduce heat exposure.[9] While there are benefits that accrue to understanding urban heterogeneity, and to acknowledging that biophysical and social patterns of heterogeneity may affect each other, the approach to heterogeneity captured by this model template is nevertheless coupled and sequential. It cannot, and does not, capture coproduced social-ecological change.

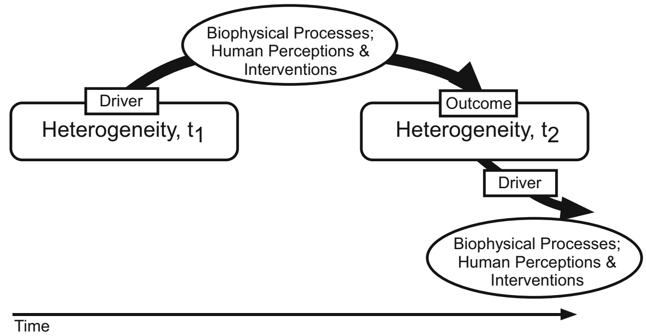


Fig. 6 A general schema for the coproduction of spatial heterogeneity in social-ecological systems through time. Heterogeneity at time 1 is acted on by biophysical processes and is simultaneously subject to human perceptions and interventions. Together these ecological and social phenomena generate the heterogeneity that exists at time 2. The spiral of heterogeneity can be represented as the alternation of heterogeneity as driver and outcome based on coproduction

In contrast to the ratchet of heterogeneity that is implied by the template in Fig. 5, an alternative exists. In recent work by Pickett et al. (2017), here included as Fig. 6, the temporal dynamism of urban ecosystem heterogeneity is represented in a time series. The system changes across distinctive moments, t_1 and t_2, in response to biophysical changes and human perceptions and interventions. Here, biophysical and social events may be simultaneous, and intertwined – that is, coproduced. No meaningful distinction is drawn between biophysical and social change in this model; rather, they are mutually produced under heterogeneous conditions.

To appreciate what the concept of coproduction allows, consider another example related to urban tree cover. The ongoing infestation of ash (*Fraxinus* spp.) trees across the United States presents pernicious, and multi-dimensional problem for urban ecology. The culprit is the introduced emerald ash borer beetle (*Agrilus planipennis*), which was accidentally introduced from Asia via untreated wooden shipping pallets. The emerald ash borer beetle is capable of killing all species of ash trees in the U.S.

We assert that this case is best understood as one of coproduction. Although ash trees are a component of native forests, it is as planted and volunteer individuals in the streets, yards, and parks of American cities, suburbs, and settled hinterlands that it is most socially significant. City streets are commonly planted with avenues of ash (Fig. 7), and although it is possible to save individual specimen trees through herculean efforts, the dispersion and ubiquity of domestic ash trees makes such expensive and intensive efforts impractical beyond scales larger than one or two trees. The spread of the emerald ash

[8] Important to note that an "agent" in this rendering can be abiotic, or even a policy: anything that effects a change.

[9] This example, elaborated in Huang, Zhou, and Cadenasso (2011), is based on data from Baltimore, a city where certain census block groups are hotter due, in part, to less extensive tree cover. This condition results in more sun-exposed surfaces, and these surfaces absorb heat during the day and reradiate it at night. We note that these are also census block groups that may be considered particularly socially vulnerable in other important ways, including relative income, high rates of poverty, lower levels of education, higher numbers of elderly residents, and higher residential percentages of ethnic minorities.

Fig. 7 Defoliation by the emerald ash borer in Toledo OH. Left, before infestation by the beetle (June 2006). Right, mortality of ash trees in June 2009, after infestation. Photos courtesy Daniel A. Herms, The Ohio State University

borer, and the tree mortality it can cause in stands of ash, is quite rapid. Knowledge among urban arborists about the infestation risk is extensive and widely distributed (Jennings et al. 2015).

Using the model template for dynamic heterogeneity, we contend that this suite of factors offers a clear example of coproduction (Fig. 8). To begin the spiral of interaction, the pattern of spatial heterogeneity in the distribution of planted and self-established ash trees is the boundary condition. Knowledge of the actual presence or the imminent arrival of an ash borer infestation combines with this boundary condition to guide management decisions: cut ash trees to prevent damage to infrastructure, and risk to pedestrians, from dead tree limbs and trunks; or treat extraordinarily regarded specimen individuals of ash (Mercader et al. 2015). This is the first iteration of coproduction, combining biological conditions with human perceptions of risk and value as well as human capacity to act according to those risks and values (*time*$_2$).

The actual, or projected, spatial distribution of the future urban tree canopy will depend on which management decisions are made and whether and how they are carried out. In light of this, property owners or municipal decision makers may choose to rely on the unmanaged regeneration of new trees, or they may respond by planting new trees other than ash. Again, many threads of biology and human agency intertwine at this step. Any changes in the species composition and tree canopy cover will differ, then, according to whether unassisted plant succession, or active planting of new individual trees, takes place. The sizes of individual trees that might be planted, whether seedlings, saplings, or pole size, and the identity of tree species used, will also produce changes in species composition and tree canopy cover. These factors might relate to the availability and expense of nursery stock, or to competing ideas about desirable aesthetics, or to desires for rapid canopy replacement, to name just a few factors. Again, biology and human agency are deeply entangled at this moment.

Let us return to the short example we offered in our discussion of Fig. 5, noting the relationship between extent of tree canopy cover and heat in cities. In the case of the ash borer beetle, the planting and management scenario that

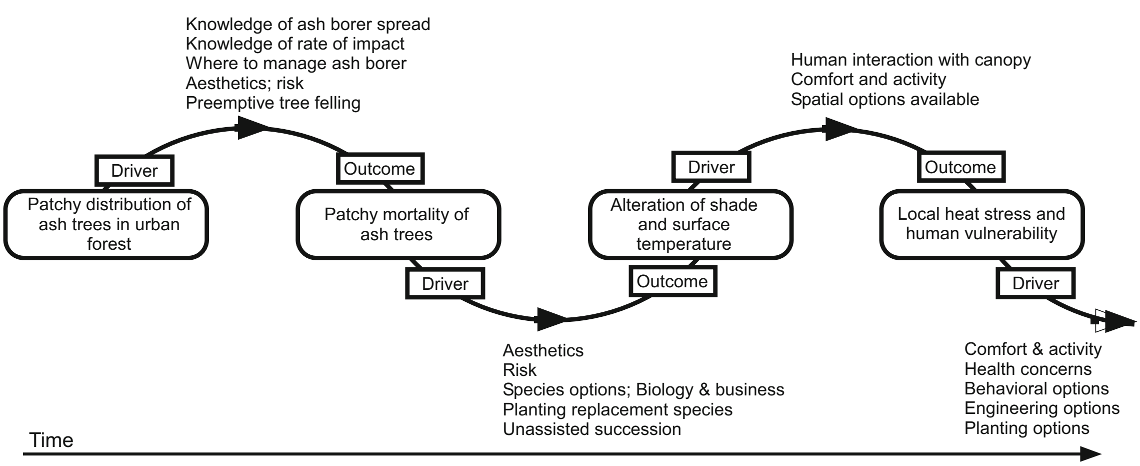


Fig. 8 The ongoing effects and responses to the invasion of the emerald ash borer beetle in North America as an illustration of the social and biophysical coproduction of dynamic heterogeneity. Drawing from the general schema from Fig. 6, we show here specific biophysical processes, human perceptions, and human interventions that can act as drivers which coproduce the next state of system heterogeneity. These are shown here as arrayed through time on the horizontal dimension

characterizes any organized response to city tree mortality leads us to expect a vast range of possible scenarios for urban forest succession, the mosaic of city areas exposed to more sunlight, and any associated increases in heat stress and vulnerability (Jones and McDermott 2015). This case clearly shows that biological components of the city do not act independently from social components, nor do they act in a clear, stepwise fashion in which a change in biology begets a clear change in a social factor which in turn changes biology. Biological status, human perception, and agency join together at each step, and heterogeneity is changed by both. This is the mutual production of social-ecological change: coproduction.

Conclusion

Social-ecological change may take place in both stepwise and simultaneous ways. By reviewing the utility and limitations of feedbacks for understanding social-ecological change, we have shown that coproduction is both a useful complement, and in many cases an essential replacement, for current urban ecology thinking. Rather than, or sometimes in addition to, *coupled* human and natural systems, we have argued, urban ecosystems often transform in dynamics of *mutual* production. Our challenge in this paper was to begin from the assumption that urban ecosystems are hybrid, and to outline how that hybridity leads to coproduction. The work that remains before us is to examine precisely how a given hybrid system is coproduced.

Coproduction helps researchers enhance their understanding of the structure-function relationships usually assumed in studies of biophysical landscape change, by more fully capturing the structure-agency relationships that characterize social change. This more comprehensive mechanism is essential for bringing urban ecologists from different disciplines closer to a shared understanding of social-ecological change, and thereby enabling a truly trans-disciplinary urban ecology.

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