Systems in Flames: Dynamic Coproduction of Social–Ecological Processes

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Ecologists who study human-dominated places have adopted a social–ecological systems framework to recognize the coproduced links between ecological and social processes. However, many social scientists are wary of the way ecologists use the systems concept to represent such links. This wariness is sometimes due to a misunderstanding of the contemporary use of the systems concept in ecology. We aim to overcome this misunderstanding by discussing the contemporary systems concept using refinements from biophysical ecology. These refinements allow the systems concept to be used as a bridge rather than a barrier to social–ecological interaction. We then use recent examples of extraordinary fire to illustrate the usefulness and flexibility of the concept for understanding the dynamism of fire as a social–ecological interaction. The systems idea is a useful interdisciplinary abstraction that can be contextualized to account for societally important problems and dynamics.

Keywords: coproduction, disturbance, social–ecological systems, systems theory, urban fire

As ecologists have increasingly turned their attention to places and situations influenced and even dominated by human actions and decisions, the entities under consideration have expanded from biological and physical to include built structures, people, and their institutions. As a result, many ecologists have engaged social analysts and developed new frameworks, such as social–ecological systems (Berkes et al. 2000, Anderies et al. 2004, Folke 2006) and social–ecological–technical systems (McPhearson et al. 2016, Grimm et al. 2017). We define *systems* in the present article as sets of specific components and their connections within a particular place and at a specific time. We recognize that this definition is abstract, and we translate this abstraction to specifics in the examples that follow.

Although the systems concept has proven to be important to ecologists, it is also used by social scientists, albeit sometimes quite differently (cf. Machlis et al. 1997, Scoones 1999, Dove and Carpenter 2007, Bird 2015, Burch et al. 2015, Orr et al. 2015, Olson 2018, Thompson et al. 2018). The social and ecological sciences often bring different assumptions to the systems concept, drawn from deep and quite different epistemological legacies. These epistemological mismatches have a long history and can often thwart productive interaction (cf. Scoones 1999, Dove and Carpenter 2007, Schoon and Van der Leeuw 2015, Rademacher and Sivaramakrishnan 2017). There may also be misunderstandings because of a temporal lag between theory in the discipline of ecological science and the discipline as it is understood by those who work in the social sciences. We discuss contemporary systems theory as it is currently used in the field of ecology to demonstrate that the meaning of system as a concept in ecology has changed over time and that, when the social and biophysical sciences share their understanding of the contemporary meanings of the concept, systems can serve as a connector rather than a barrier to transdisciplinary inquiry.

In the present article, we make two assertions. First, because the systems concept is a foundation of contemporary ecology, the concept must be continually theorized, analyzed, and revised to remain useful and relevant. Emerging climate related disturbances that contain ecological and social causes, consequences, and responses lend urgency to the need for models of social–ecological systems to keep pace with changes in the world. Systems are dynamic, and, consequently, they are conceptualized to capture the changes we expect and to anticipate those we do not. In other words, change is fundamental to the systems concept. Second, the systems concept can serve as a connector to transdisciplinary inquiry, but we must first understand and overcome misunderstandings between biophysical and social scientists about how biophysical ecologists formulate the contemporary concept (Flanagan 1993, Scoones 1999,

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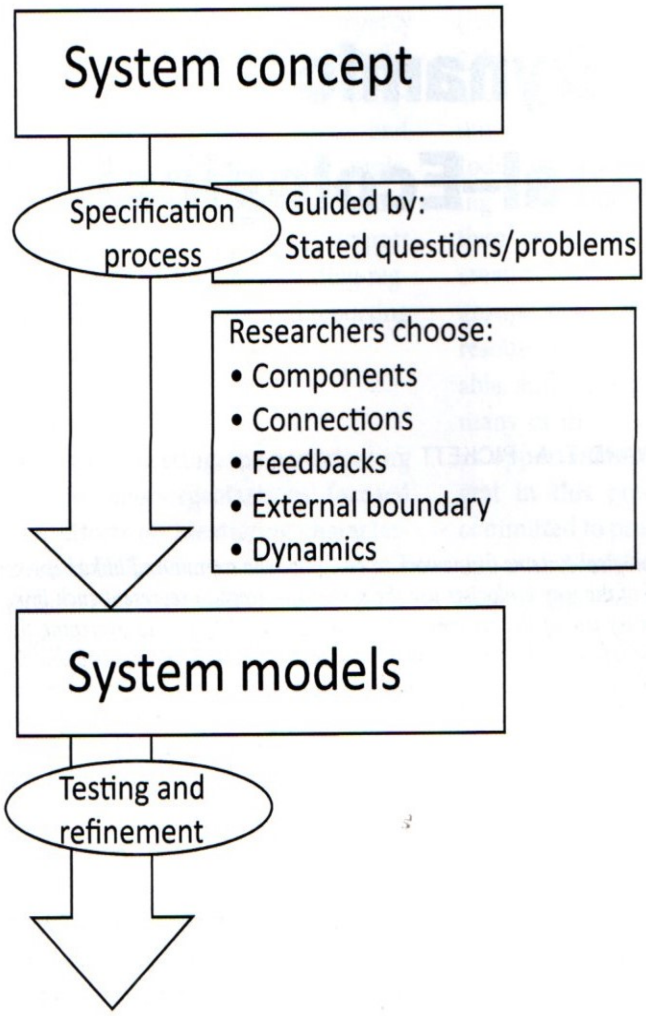

Figure 1. The relationship of the general systems concept with specific models of particular systems. The process of specification, conducted by researchers or stakeholders is guided by a question or process that sets the domain of the specific models. The components of the system, hypothesized connections and feedback loops, the spatial extent or boundary, and the dynamics inform model content and structure. The hypothetical fire-system models presented in table 1 are examples of specific systems models that combine social and biophysical structures and processes relevant to their particular contexts. System models can then be tested and refinements made.

Dove and Carpenter 2007, Judd 2011, Simpson and Kelly 2011, Orr et. al. 2015). Therefore, the present article is intended for two audiences: social scientists who wish to better understand how the systems concept is used in the field of ecology today and ecologists who engage with social analysts and may be similarly interested in building better mutual understanding.

To ground our assertions, we point to the very timely example of wildfire and its changing dynamics in many parts of the world. We use this example to demonstrate the capacity of the contemporary systems concept to accommodate these changing dynamics. Such dynamism is recognized by many (e.g., Collins et al. 2011, Andersson et al. 2021, Kasperski et al. 2021). Although we are not fire ecologists, we use the changing dynamics of fires in urbanized places to demonstrate how specific models of social–ecological systems can lag behind changes in the world and, therefore, constrain how society views and reacts to fire as an extreme event, often with catastrophic consequences for people.

What a system is (and isn't). Systems have remained an important and valued concept in the ecological sciences. In the present article, we provide a general review of the contemporary concept and the way it has evolved in biophysical ecology and the social sciences. This review will allow us to emphasize the dynamism of the concept and to explore commonalities and differences in how the disciplines tend to use it, in an effort to move beyond misunderstandings.

The contemporary concept in biophysical ecology has expanded and changed to recognize systems (Simberloff 1980, 2014, Pickett et al. 1992) as maintaining porous boundaries and therefore open to material and informational influences that arise from outside and may in fact regulate the system; lacking a fine-scale stable equilibrium point and instead experiencing internally and externally generated disturbances and disruptions; changing through probabilistic or contingent dynamics; and inclusive of human action, agency, and influence, both current and as legacies.

When these attributes of the systems concept are differently interpreted or understood by social analysts, the fields may employ the term in very different ways. This may be fueled, in part, by a lack of interdisciplinary communication about how the meaning of systems has changed across fields over several decades. Systems may be misconceived by critics as static or fixed locations surrounded by hard boundaries; they may also be thought to provide fully encompassing, or *totalizing*, representations of all relevant processes (Stojanovic et al. 2016). Systems may be further misconstrued as offering deterministic explanations as opposed to accommodating flexible human agency, seeking equilibrium after a set pattern of change, and intending to be universal or applicable to all places at all times. We agree that these views of systems severely limit the interdisciplinary utility of the concept.

There are several other ideas worth emphasizing about the current ecological epistemology of systems. First is the fundamental idea that the system as a general concept must be translated to apply to specific situations (figure 1). To accomplish that translation, a system model must be specified. Models can take many forms. They can be diagrammatic boxes and arrows, graphical, or mathematical, for example. Regardless of form, models are intended to organize thinking and expectations about a place or situation, to structure hypotheses, and to guide testing. The system model places the concept into its specific context (Pickett and Cadenasso 2002). Initially, system models are viewed as tentative. It is expected that system models will continuously change as new insights are learned about the situation of interest or as the model is applied to and tested in other places or times. To begin developing a systems model, researchers or practitioners must identify the system components. Second, the connections among the components must be explicitly chosen. This step satisfies the concern of researchers with theoretical or supported hypothetical connections. Not all interactions that might appear in the system will be consequential. Third, the researcher must state the scope of the system. That is, researchers and practitioners will recognize a chosen or perceived boundary for their theoretical or practical purposes. A chosen boundary may be adjusted as needs change or as more is learned about how the system actually works. The people using the specific system model must be aware of the exchanges that cross their chosen boundary. Finally, system models are refined as they are tested or applied to new spatial and temporal contexts (figure 1; Pickett and Cadenasso 2002). Alternatively, if their system model emphasizes connections rather than spatial limits—that is, it primarily takes the form of a network—the empirical emphasis will be on the flows over a more extensive space rather than dynamics within a chosen boundary. Even with a focus on a delimited place, researchers should not neglect long-distance connections or the effects of the porosity of the chosen boundary (e.g., Peters et al. 2008, Meyfroidt et al. 2013).

Because biophysical ecological system models are flexible and contingent, they have an express advantage in bringing the social and ecological sciences together. Rather than couplings of distinct social and ecological subsystems (e.g., Redman et al. 2004, Collins SL et al. 2011), they are literally a single coproduced system that is reproduced by interactions among its social and ecological features (Rademacher et al. 2019). The main point is that ecological systems, in the contemporary, nonequilibrium, or open and open-ended sense, are coproduced, meaning that social–ecological transformations are mutually and simultaneously generated rather than generated through a series of stepwise feedback loops (Rademacher et al. 2019).

We now explore how this contemporary, refined view of the systems concept can better facilitate collaboration between the social and natural sciences. Social sciences and ecological sciences both focus on interactions, influences, agency, and change. We consider fire, a familiar but diverse kind of disturbance that affects both the social and ecological aspects of systems, in order to examine whether there are commonalities between social and ecological epistemologies of complexity, production of environment and meaning, and change. Our central concern in the present article is not the fires, per se, but how to conceptualize the interaction of shifting fire behaviors, their impacts, and social responses that accompany them by employing a contemporary systems approach. We will then deepen the analysis by examining how these commonalities can be reinforced by critically thinking about systems theory (e.g., Orr et al. 2015, Schoon and Van der Leeuw 2015) and taking a coproduction approach (Rademacher et al. 2019). Unifying social and ecological understanding of systems will have both practical and theoretical benefits for analyzing and managing complex social–natural processes.

Contemporary fire as an extreme event. The need for and value of the flexible contemporary systems concept is illustrated by the evolving nature of extreme fires (Goss et al. 2020, Collins L et al. 2021, Ellis et al. 2022). The year 2020 was notable for the number and size of fires around the globe that had catastrophic results for affected people and communities. Conspicuous and seemingly unprecedented examples were the extraordinary fires in the Mediterranean climate zones (e.g., figure 2) of North and South America, in southern Europe, and in Australia. In addition, extensive and extreme fires occurred in montane and subalpine forests of the American West, boreal conifer forests of the far north, and in tropical forests usually thought to lack fire. Scholarship mirrors the headlines (Bowman et al. 2017, Covington and Pyne 2020), and press reports, including interviews with fire experts and firefighting authorities, confirm that the 2019–2020 fires, in terms of the number and total acreage burned, were well beyond the experiences of recent decades and, in some cases, centuries (e.g., McLauchlan et al. 2020, Norman et al. 2021, Iglesias 2022). In addition, the fact that such extremes were so widely distributed across the globe and touched not only seasonally dry but also moist ecoregions underscores the human significance of these events (Covington and Pyne 2020).

A second dimension of the severity of human impact of fires relates to the changing nature of the interface between settlement and wild lands (Theobald and Romme 2007). Many of the extreme fires burned in inhabited places at or near the fringes of savannas, woodlands, and forests (Moritz et al. 2014, Radeloff et al. 2018). Collectively, these inhabited situations can be called wildland–urban interfaces (WUIs; Martinuzzi et al. 2015). Although such zones have become common locations of wildfire threat and control, these zones are expanding (figure 3; e.g., Alcasena et al. 2018, Radeloff et al. 2018, Godoy et al. 2019), and the recent spate of fires consumed not only individual homes or sparse neighborhoods constructed on the WUI but entire towns in forest and woodland landscapes (CAL FIRE 2020a). The loss of life, livelihood, shelter, and infrastructure can only be described as extraordinary (Duane 2020). Social capital has also been lost (Kolden 2020); the communities are dispersed, and people must reestablish their lives in new places where they cannot rely on familiar networks and livelihoods (e.g., Hansen 2019). We aim to evaluate the use of the systems concept to link social and ecological sciences, and we engage the changing dynamics of these fires as a timely example of a coproduced social–ecological system.

The changing nature of fire's catastrophic impacts. Contemporary fires have catastrophic results, in part because of direct human and institutional actions. The increasing penetration of suburban or villa-style residential development, not only at the WUI but also in more remote natural

Figure 2. Map of extent of catastrophic wildfires in California, United States, 2020. Source: Reproduced under a Creative Commons license by Phoenix7777. Data source: MODIS Active Fire Detections for CONUS (2020), Geospatial Technology and Applications Center, US Forest Service, US Department of Agriculture. Shapefile: modis_fire_2020_272_conus_shapefile.zip (through 272 day of the year, 28 September). Map: Open Street Map, CC BY-SA 4.0 International, https://commons.wikimedia.org/w/index.php?curid=94591083.

vegetation beyond, is one cause (Syphard et al. 2007). This increases the interaction of human activities and vegetation that may spark fires in many ways, including stringing power lines through vegetation, recreational fires, the use of power tools, parking vehicles on dry grass, and tow chains dragging on pavement. In some forests, decades of fire suppression have increased the density of understory vegetation that serves as fuel during drought (e.g., Ellis et al. 2022).

Over recent decades, social systems have adjusted to fire at the WUI by instituting new building codes, such as fireproof roofing materials, and the avoidance of landscape plantings adjacent to homes and buildings (Syphard et al. 2014). There are also growing pressures to employ controlled burns to thin understory vegetation (Covington and Pyne 2020). This practice attempts to mimic the documented fire patterns that would have prevailed before the era of pervasive fire suppression. Fire vulnerability is also increasingly dispersed as settlement patterns spread limited firefighting resources over large areas, and complex topographies at or beyond the WUI can also reduce the effectiveness of firefighting on the ground (Ferguson 2017).

Several environmental influences have contributed to the extraordinary number and size of the recent fires: general regional warming, lengthening of the dry season, changes in onset of dry seasons, shifts in precipitation and storm patterns, and increasing severity and lengths of interannual drought (Abatzoglou and Williams 2016, Hessburg et al. 2019, McLauchlan et al. 2020, Duane et al. 2021). Of course, these are generalized characteristics, and specific aspects of these conditions or interactions among influences are important (Schoennagel et al. 2004, Keeley and Syphard 2019). Under these altered regional environmental conditions, the fires themselves often behave differently than those in the past. The fire literature is beginning to deal with these new realities (Bowman et al. 2017, Duane et al. 2021), and several features clearly play a role. Extraordinarily large fires essentially create their own weather (Jones and Carvalho 2020, Simon 2020). The columns of air above these large fires become superheated and rise to extraordinary heights in the atmosphere. As cooler air is drawn toward the low pressure created by the rising column of fire-heated air, surface winds can attain velocities usually associated with severe storms. These strong surface winds feed more massive heated updrafts that remain hot for longer times as they rise. Therefore, these winds can lift much larger firebrands and keep them and smaller embers hot. Such large, hot materials can become ignition sources at unusually long distances beyond the front of the fire itself. The phrase *fire tornado* evokes something of the extraordinary power and energy these new fires can generate and maintain because of internal feedback loops (Jones and Carvalho 2020).

One reason that the recent fires are so socially catastrophic is that they seem resistant to standard firefighting strategies developed for the WUI. Wildfire control usually relies on containment. Firebreaks and backfires have been key to this strategy: Keep the fire bottled up in the area where it has already consumed most of the available fuel. The firebreaks usually provided by paved roads or streams or even those constructed

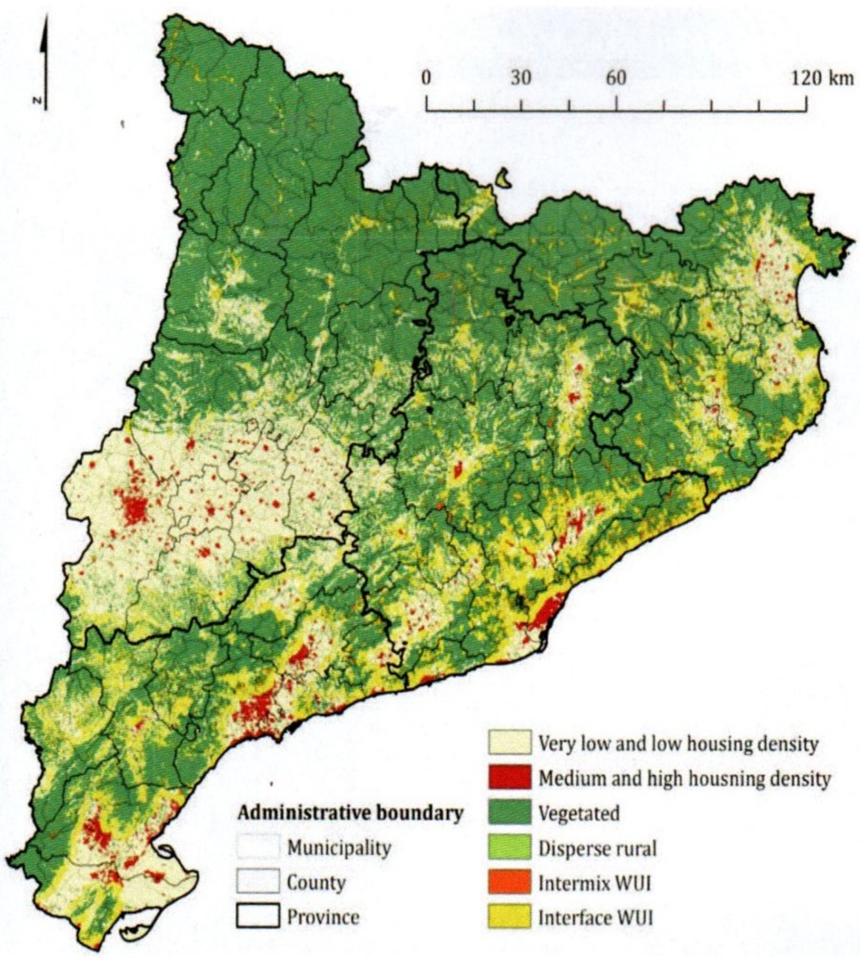

Figure 3. Interdigitating houses and wild or semiwild vegetation at Urban Wildland Interfaces in Catalonia, Spain, in 2018. Source: From Alcasena and colleagues (2018). Reproduced under Creative Commons license CC BY-SA 4.0 International by Fermin J. Alcasena, Cody R. Evers, Cristina Vega-Garcia. Data source: The wildland-urban interface data set of Catalonia. Also see aerials in original data article at https://doi.org/10.1016/j.dib.2017.12.066.

by firefighting crews in wildlands often fail to contain these new extreme fires. The firefighting establishment is working to develop new strategies in the face of these unprecedented events (Thompson et al. 2018, CAL FIRE 2020b), and it is no surprise: The new fires combine complex social phenomena, natural phenomena, and feedback loops in wholly novel ways.

The complex relationships these fires exhibit can be conceived as networks of social and ecological processes or systems. Again, the factors and their dynamics are changing, so a static or closed view of systems is inappropriate. However, a contemporary view of the systems concept—one that employs recent, active ecological ideas about systems (Brown and Rounsevell 2020)—can be useful in thinking through the intellectual problems that the socially catastrophic fires highlight.

Here, we point to some illustrative contrasts in the fire–society dialectic. We have already discussed the contemporary catastrophic fires that have come to characterize the WUI. To further illustrate the potential of the systems concept as a tool to understand social impacts of disturbance, we now describe a well-documented historic urban fire—the Baltimore fire of 1904. This example illustrates the specification of a general theoretical framework to a defined situation in time and space, and also informs a hypothetical urban fire model later in the discussion.

A coproduced urban fire: Baltimore, 1904

The Great Baltimore Fire shows how a careful and open-ended systems approach can expose important features of a coproduced, human–natural disaster. It is social because several components are direct or indirect outcomes of human decisions, planning, and social capacities such as firefighting strategies, equipment, people, and regulations; it is natural because it deals with the same components as nonurban fires such as temperature, wind, water availability, and physical configuration of system structure. Although we focus on Baltimore, catastrophic fires have happened, are happening, and will happen in different social contexts around the globe. The model we construct in the present article is based on a specific fire–society relationship in Baltimore at the turn of the twentieth century. Although fire–society models in other places are expected to differ in their specific components and interactions, this example from Baltimore illustrates the construction and utility of coproduced system models. Our narrative summary of the key aspects of this fire was informed by the work of Olson (1997), Petersen (2004) and Hoffer (2006).

The precise ignition source of the Baltimore fire on 7 February 1904 is uncertain. That it started in the masonry John Hurst and Co. dry goods building is undisputed. A prevalent version of events relates how the fire could have been lit by a cigar butt dropped through a missing lens on a sidewalk vault light. In the nineteenth century, thick lenses of glass, about 2 inches in diameter, were set in iron frame matrices to provide natural light to basement spaces beneath sidewalks. Although these glass lenses were quite thick, they occasionally broke under the traffic of pushcarts and the like. Perhaps one of these voids admitted a casually discarded cigar stub by someone out for a stroll on that Sunday morning. It was a frigid, windy day, and haste may have been more on the stroller's mind than care of fire.

Whatever the source of the spark, goods stored in the basement ignited, and an automatic alarm sounded at 10:50 on Sunday morning. The fire department was soon on the scene. As a fire company entered the building, the sound of slamming doors alerted the commander to a strong

Figure 4. Ruins of downtown Baltimore after the 1904 Great Fire.

updraft in progress. He ordered his firefighters to retreat. Moments later, the fire, rushing up through the elevator shafts and stairwells, exploded and essentially turned the six-story building into a torch. Sparks and embers wafted from the broken windows, and the roof, soon aflame, created still more hot debris that spread on the updraft of hot air. Downwind, firebrands ignited other buildings from the roof down, spreading the fire rapidly. The water pressure of the fire engines was insufficient to reach beyond the second stories in many streets.

Baltimore was the sixth largest city in the United States in 1904, and its downtown was a mosaic of the industrial city, interspersed with the legacies of nineteenth century mercantilism. Lumber yards and banks were adjacent, kerosene stores and commercial warehouses were close neighbors, and dry goods establishments and coal yards shared the same blocks. It was an object lesson in fire theory: On ignition, the fuel, heat, and oxygen mixed quite freely.

Fire companies from Washington, DC; Philadelphia; and even as far as New York City responded to urgent telegrams calling for help on Sunday afternoon, but their fire hose couplers did not fit the threads on the Baltimore fire hydrants. The quickest remedy was to stuff canvas in the fittings in an attempt to make a tight seal. At best, the result was reduced water pressure in the hoses and weak streams of precious water. A machine shop in the industrial Locust Point neighborhood, well south of the burning downtown, rushed to make adapter fittings for the visiting fire companies.

The fire finally went out at 5 p.m. the next day, when the wind changed direction and pushed the fire to the banks of the Jones Falls stream. The channel was armored with stone and lined with mills and factories. In this fortuitous firebreak, firefighters from Baltimore and several departments from afar held the line.

When the fire was finally extinguished, 140 acres of the core of downtown Baltimore were smoking rubble (figure 4). Masonry and steel frame buildings that had been thought to be fireproof were stark ruins against the sky. The streets and alleyways were choked with piles of bricks from collapsed walls, which had severely impeded the access of horse-drawn firefighting equipment. The dense courses of telegraph and telephone wires lay in tangles, encased in the ice formed from the streams of water that froze on contact with the wires that stood between the fire engines and the flaming facades.

The results of the fire were far reaching. The shoreline of the harbor was reshaped as the abundant debris of the fire was used to make new land. Many downtown streets were widened to promote more rational traffic flow and improve emergency access. Zoning regulations were ordained to separate storage of combustibles from commercial and business properties. Cross-jurisdiction standardization of fire hose

Box 1. Social and ecological factors contributing to fire vulnerability or response.

The factors can be positive (+) or negative (–)

Prefire Baltimore

– No zoning for separation of combustibles and other uses
– Local specification of fire hose fittings
– Legacy of colonial and early federal era street dimensions and layouts downtown
– Few fire department commanders
+ Effective communication with other cities
+ Local indemnification
+ Automatic fire alarms in some buildings
+ Experienced, professional fire department

The event

– High winds
– Freezing temperatures

Contingencies

+ Sunday rather than workday occurrence
+ Wind patterns kept fire downtown
+ Wind shift drove toward Jones Falls firebreak
– Early sidelining of a senior fire department commander by injury

and hydrant fittings was undertaken, although, to this day, there is no completely uniform national standard.

In the wake of the fire, the strong rural interests in the Maryland legislature finally allowed the city of Baltimore to raise funds by issuing its own bonds. This right had been jealously withheld previously but now was seemingly unavoidable. As a result of the physical opportunities created by the fire and the desires of the city elites to modernize and to join the fashionable City Beautiful movement of the time, many changes emerged in Baltimore. A plan for a network of parks and parkways, designed by the prestigious Olmsted Brothers landscape architecture firm and the construction of a new sewer system that separated sanitary and storm drainage were conspicuous outcomes. Baltimore was very late among American cities in constructing a sewer system, but that ironically allowed it to create separate storm and sanitary systems—an unusual condition in older American cities to this day.

Transforming narrative to a systems model. The story of the 1904 fire in Baltimore is a rich and compelling narrative. We propose that it can also be represented as a dynamic, social–ecological system model. It forcefully demonstrates the coproduction of the disaster by interacting social and environmental phenomena. A summary of key points that can inform a systems model of that fire are contained in box 1.

All these factors can be assembled into a hypothetical systems model using a template (figure 5) developed in ecology under the rubric of disturbance (Peters et al. 2011, Grimm et al. 2017). The form of the model emphasizes that there is an event that embodies specific mechanisms that may disrupt the structure of a system or place; a preexisting system structure, a network of joint social–biophysical interactions that has a given capacity to resist or respond to the mechanisms of potential impact; and the properties of the system that influence its response to the fire disturbance. These interactions can be diagrammed as a system model specific to the conditions of the 1904 Baltimore fire (figure 6).

Several important insights emerge from this conceptualization of fire as a complex disturbance process through time (e.g., Grimm et al. 2017). First, the fire is not simply the triggering event but, rather, the interaction of an event that embodies kinetic or energetic mechanisms with a structure whose capacities determine how that structure might change as a result of the impact. A spark as a potentially disturbing event will do nothing to an entirely stone structure but can ignite a dry, timber framed building. In other words, whether there is a disaster or not will depend on how the energetic event—the spark—interacts with the structure of the place of interest. Such structure includes social and institutional components.

A key point is that, in coproduced systems, a disaster is neither only natural nor only social but a combination of the two. Fire and other disasters in settled landscapes are always coproduced by social phenomena and biophysical phenomena. There is no such thing as a natural disaster in a place that people have built or have altered by their management or subsequent neglect. Many scholars have made this point in researching disruptions to social–ecological places before (Vale and Campanella 2005). Hurricanes (e.g., Bullard and Wright 2009), riverine flooding (Berry 1998), earthquake (Vale and Campanella 2005), heatwaves (Duneier 2004), and tornadoes (Brown et al. 2016), among other events, exhibit the hybrid biophysical and social

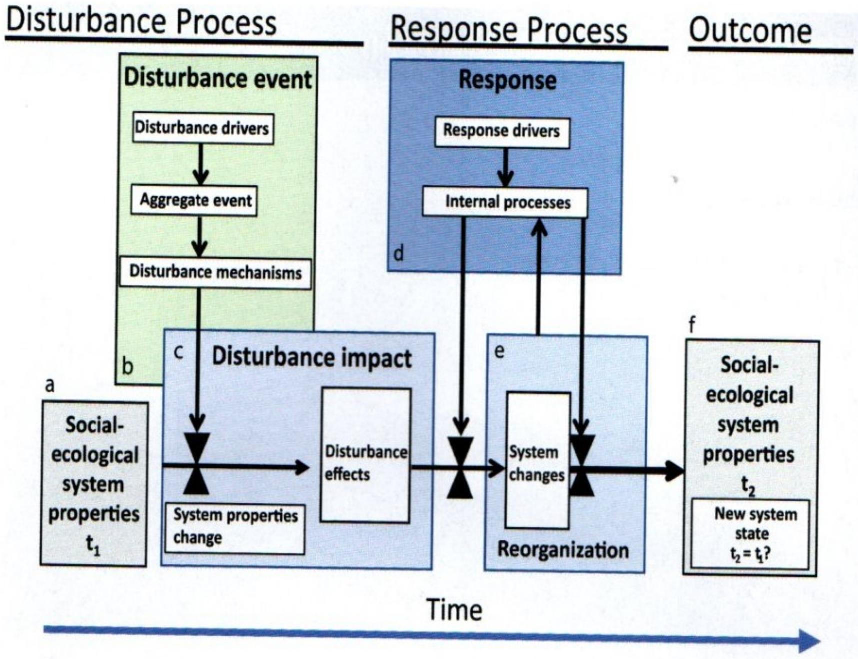

Figure 5. A template to guide creation of a specific system model, such as that of the 1904 Baltimore fire. A specific system model for a disaster such as an urban fire would include (a) the coproduced social and biophysical structures, composition, and links of the site prior to the fire; (b) the characteristics of the disturbance event, including its environmental drivers and context, the aggregate characteristics of the event, and the mechanisms by which the event can interact with the system; and (c) the coproduced impact of the interaction of the event with the preexisting system structure. The response to the disturbance impact (d) is also coproduced and governed by processes described as a recovery or reorganization (e). The subsequent structure of the site can be different or similar to the predisturbance site (f). Key features that populate this model structure are described in box 1 and illustrated in figure 6.

nature of disasters, catastrophes, and disturbances. So, although this is not a new insight, an open-ended, inclusive systems approach can help explain and link the processes and can help prepare residents, managers, policymakers, and researchers for the hybridity and dynamism of such events (Pickett et al. 2017).

There are diverse fire–society relationships. Fire–society relationships, such as those exposed in the 1904 Baltimore fire model (figure 6) can differ from place to place even within cities and have changed through time. We suggest that the characteristics of familiar urban fires (e.g., Hoffer 2006, Bankoff et al. 2012), such as the Baltimore 1904 case, differ from the conflagrations now consuming entire WUI settlements (e.g., Boghani 2019). Although a thorough review of the growing literature on the changing dynamics of fire is beyond our scope (cf. Pyne 2021), we propose four idealized and necessarily simplified models to exemplify how the system concept is open-ended and adaptive. The goal of these models is to reveal social and ecological connections of the coproduced system. An improved understanding of coproduced systems might be translated into the civic realm to support the public, policymakers, and the firefighting establishment as their state-of-the-art thinking evolves to enable societies to address the novel problems of increasingly catastrophic human impacts of extreme fires (Thompson et al. 2018).

Hypothetical social–ecological fire models

The multiple ways that cities and fires interact can be addressed using conceptual tools we label *fire-system models*. We use these hypothetical models to illustrate key contrasts in the fire-society dialectic but also to put the contemporary systems approach into action. We emphasize that fires occur in specific contexts, and, although we invoked the Baltimore fire in order to construct a specific urban systems model, we acknowledge that the model specified in other places would differ. For our purposes, we recognize four simple models that describe idealized fire–society relationships (table 1). Our models parallel the global and deep time analyses of Pyne (2015, 2021) but our framing differs because we focus on urban situations. These models are intended to organize our thinking about this dialectic, not to represent uniform maps of whole cities. Such model contrasts can exist across space or time. Importantly, they do not represent a deterministic or universal developmental sequence but are way points in the multidimensional thinking about complex fire–city interactions. The first three models can be mapped within cities, whereas the fourth model engulfs the meaningful heterogeneity within a single urbanized place. To show how this idea works, we begin with the contrast between the flammable district and the fireproof district.

The flammable district

Flammable urban districts, at their most extreme, are built of readily combustible materials, such as timber and thatch, and burn in synchrony with the natural or agricultural lands in their surroundings (Pyne 2021). Fires ignited during dry seasons, drought, and lightning storms characterize flammable districts. Fire prevention mainly depends on household actions, and similarly, firefighting likely involves household members or near neighbors. Although this model was very characteristic of early cities, many megacities now spreading worldwide also contain flammable districts. Examples include the self-built shanty towns constructed of highly flammable found materials in cities around the world. Flammable districts can be exemplified by the informal settlements within Cape Town, South Africa, in which shack fires are common (Maritz et al. 2012). Flammability in

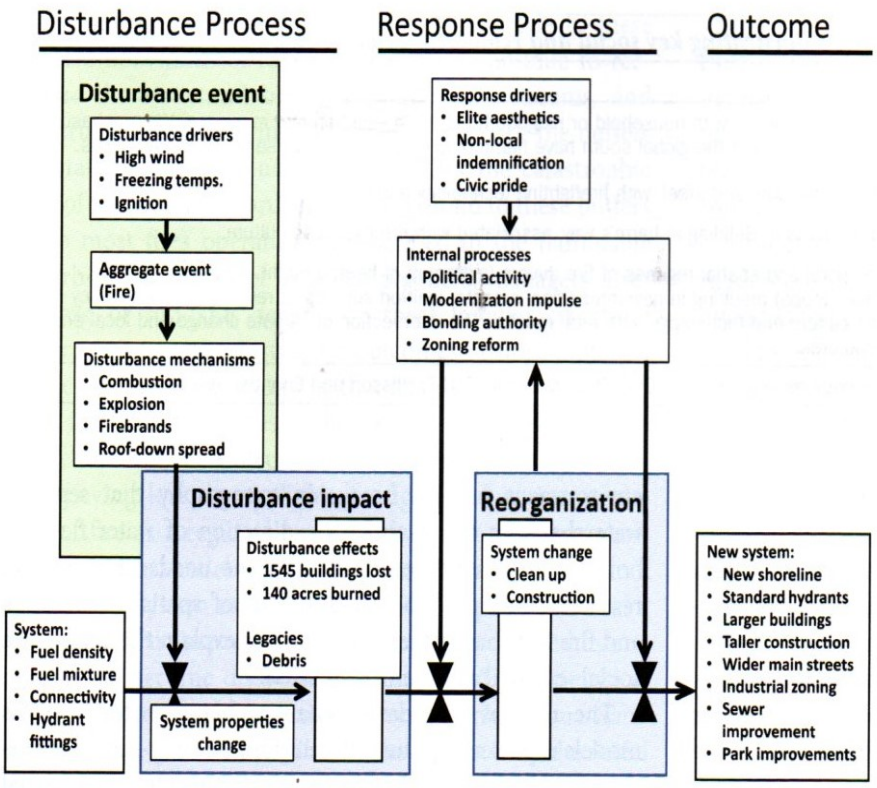

Figure 6. A specific system model for the 1904 Baltimore fire.

such places is exacerbated by a lack of infrastructural tools to contain or extinguish fire or poor access by mechanized firefighting equipment via the narrow lanes or steep topography. As was expected, the flammable districts model has both ecological and social components.

The fireproof district. The fireproof district contrasts with the flammable district in both material and social conditions. Cities or districts adopt features considered fireproof, such as masonry walls, tiled roofs, and piped water, along with policies and social organization to fight fires that do break out. The fireproof district may minimize wooden structures in the urban fabric and reduce the use of live fire for heating and cooking in hearths or kerosene stoves. Furthermore, the mixing of fuel depots, coal yards, kerosene stores, and lumber yards with commercial and residential buildings tends to be reduced in fireproof districts. Social features of the fireproof district also appear in the formal organization of firefighting that compensates for the piecemeal emergency response of the flammable district. Professionalized fire departments, mechanized equipment, and well-distributed fire hydrants are common aspects of fireproof cities or districts.

Widened streets that facilitate access by fire engines, standardized fire hydrant fittings to take advantage of intercity cooperation in emergencies, wire reinforced glazing to reduce the spread of sparks and embers through windows broken by explosions or heat stress, and altered zoning to separate the highly flammable businesses from the commercial and residential districts are features found in many fireproof districts. Such changes were instituted in Baltimore following its 1904 fire. Again, a mix of interacting material features and social processes characterizes the fireproof district.

The flammable suburb or exurb. A third major interactive human–natural fire model can be called the flammable suburb or exurb. This model is appropriate to a highly dispersed urban fabric, such as that produced by the explosive growth of postwar suburbs in the United States. Such sparse suburban–exurban patterns are associated with a large commuting radius that stimulated the placement of housing in formerly rural or uninhabited lands. In Mediterranean climates or dry montane zones throughout the world, new housing has been built adjacent to or within vegetation types such as chaparral, maquis, matorral, bush, or dry conifer woodlands that have long accommodated and adjusted to wildfire. These hybrid landscapes of semiwild or wild vegetation studded with suburban and exurban villa-style or isolated homes is common enough to be identified by a name cited earlier: the WUI (figure 3).

The relevance to fire in this third model is that many of the newly urbanized vegetation types have evolutionary adaptations to recover after fire and a corresponding ecological history of dependence on fire. Inevitably, such vegetation will burn, as a result of either human error or human intention or as a result of natural ignition by lightning. In some regions, a policy of fire suppression or a reduction in agricultural or pastoral livelihoods allowed fuel accumulation in the plant communities of the WUI. This leads to larger fires that demand a vast institution of wildland fire fighting. The goal of the resultant firefighting strategy on the WUI is containment. Ultimately, contained fires often die down in cooler weather sometimes associated with rains and reduced winds. Containment exploits existing firebreaks, the laying of new firebreaks, and waterbombing from aircraft. The rugged terrain of many of the most attractive exurban lands worldwide makes the containment by both earth moving equipment and manual labor difficult and slow. Again, this fire model combines ecological phenomena and social structures and responses to the nature of the risk.

Flammable urbanism. There have always been some fires that tested the limits of the firefighting strategy in the flammable suburb or exurb model. But the widespread extreme fires that we described earlier present a new combination of ecological influences and consequent fire behaviors. A new and emerging fire model is suggested by the details that experts have so cogently brought together (e.g., Barbero et al. 2015, NOAA 2020, Norman et al. 2021). They note that the intensity, size, and feedback loops by which recent extreme fires

Table 1. Four hypothetical fire system models illustrating key social and ecological components.

Model type	Key features
Flammable district	Settlements of timber and straw, with household or neighborhood fire prevention and response. We emphasize that some contemporary cities in the global south have flammable districts such as self-built shanty towns.
Fireproof district	Cities and suburbs of masonry and steel, with firefighting technology and culture.
Flammable suburb or exurb	The urban–wildland interface. Building in harm's way, associated with fire exclusion culture.
Flammable urbanism	Unprecedented temporal and spatial regimes of fire drivers (extremes of heat, drought, wind, dry lightning, internal fire feedback loops) resulting in new intensities, extents, ignition sources. It reveals the inadequacy of existing firefighting culture and technology, with fatal results. The intersection of climate change and local and regional urban structures.

Note: These are hypotheticals derived from various sources (e.g., Hoffer 2006, Bowman et al. 2017, Nilsson and Enander 2020).

generate their own weather demand a new understanding of the ecological and social interactions.

For instance, climate change appears to be generating more dry-lightning storms, in which the potential for ignition is typically disconnected from the likelihood of rain. The assumptions of how most fires were started therefore does not translate fully from the flammable suburb or exurb model to the current reality. Similarly, the spread of fire by the fire-generated tornadic winds, with their extraordinary ability to disperse even very large firebrands over great distances, differs from the expectations of the third fire model, focusing on the flammable suburb or exurb. These new mechanisms act as a syndrome of processes—a system—that limit the success of the approaches to fire containment (e.g., Thompson et al. 2018). Although containment often worked in the past to manage the fire threats at the WUI, these new monstrous fires seem to call for a regional strategy. The firefighting policy and management communities are working diligently to formulate new understandings and practices to deal with the novel fire system (Simon 2020).

We can now unambiguously use the word *system*, in a contemporary and nontotalizing sense, to describe the functioning syndromes of complexities and dynamics illustrated by the flammable district, the fireproof district, the flammable suburb or exurb, and, finally, the emerging system that characterizes flammable urbanism. These are four different and specific systems models. They are propositions that identify the social and ecological factors that seem most relevant to each kind of human–fire interaction. They are associated with such things as urban form, larger landscape context, external driving factors such as climate and extreme drought but also with how fires are conceived of, prevented, and fought (Ferguson 2017). These systems models are specific expressions of the general idea of a system, but each one represents different particular combinations of urban social and material features as they interact with different kinds of fire behavior (figure 5).

Dynamism of boundaries in the systems models

As a reminder, a key component of systems models is the boundary that delimits what is considered in or out of the system. Boundaries can be determined by the physical environment such as breaks in topography that separate watersheds on the basis of the direction of water flow, or boundaries can be determined by the needs of a specific research question. The relationships of spatial boundaries and fire in urban places helps further explain the utility of a social–ecological systems approach.

The role of boundaries changes between the systems models representing the different kinds of city–fire relationships. In the flammable suburb or exurb model, the internal boundaries are expressions of the spatial structure of the WUI. How the interface is structured around specific buildings or around clusters of buildings plays an important role in firefighting (e.g., Syphard et al. 2014). The removal of shrubs and trees near buildings and the clearing of brush and vegetation debris in yards, in essence, sharpens the structural boundary between the wild fuel and the buildings to be protected from fire. In addition to using these structural boundaries, firefighters sometimes depend on paved roads and highways as firebreaks. When these are inadequate, firefighters and their partners use earthmoving equipment or manual labor to establish new boundaries or firebreaks at strategic locations in the landscape. Choosing where to establish (hopefully) functional boundaries in a burning landscape imposes a structure on the basis of social decisions of value, risk to life and property, and feasibility. This combination of found, built, or newly created firebreaks as examples of internal boundaries shows the relational nature of boundaries. Even boundaries chosen initially because of structural distinctness are intended to reflect or manage functional processes and relationships to fire.

The role of familiar internal boundaries in the emerging fourth fire model is quite different, because flammable urbanism involves such extreme fire dynamics and behaviors. The recent catastrophic effects of fires, which call for a new fire system model, flammable urbanism, do not interact with the internal boundaries that the previous model (the flammable suburb or exurb) recognizes and depends on for effective fire control. The roads, cleared buffers around houses, streams, and constructed firebreaks that help control fires in the flammable suburb or exurb, simply do not operate the same way in the face of the regionally powered fires. The finer scale boundaries that can be counted on to contribute to fire containment in the flammable suburb or exurb model at the WUI are essentially invisible in these massive new kinds of fires. Humans may continue to recognize the structural boundaries of roads, streams, and constructed firebreaks in landscapes, along with the buffers maintained on individual house lots. But the catastrophic fires of flammable urbanism do not respond to these buffers as do most fires operating as described in the flammable suburb or exurb model. Nor can planners, managers, firefighters, or residents depend on these familiar structural features to control catastrophic outcomes of fires. Note the subtle shift in terminology in that last sentence. What had been internal boundaries in the flammable suburb or exurb model become mere structural details in flammable urbanism, having lost their reliable firefighting function in the face of fire as a regional juggernaut. An internal boundary in one system model does not necessarily serve as such in a contrasting system model. Another way to put this is that a particular structure and a function can be associated in one model but become dissociated in another. This discussion reveals that neither boundaries nor systems models are static or totalizing, to use the familiar critical terms from the social sciences.

Because the fire system represented by the catastrophic fires in urbanized regions does not permit the continued reliance of familiar structural boundaries, socially strategized boundaries will have to substitute. For instance, if cleared buffers around houses are not reliable, the boundary may become one of speedy early evacuation rather than defense of individual buffered houses. If traditional larger landscape boundaries do little to halt the spread of massive fires that waft basketball-size embers high into the winds, strategies other than ad hoc firebreak construction may have to be put in place to protect the lives of firefighters and residents. If the WUI has been thought of as a relationship of individual houses or clusters of dispersed houses to wildland fire, a new conception of larger landscape structure may have to be used to account for the risk now faced by entire towns and settlements (Syphard et al. 2014). Given that structural boundaries have been so important in the flammable suburb or exurb model, their erasure by the fires motivating the new flammable urbanism is socially significant. Boundaries may be important for deciding what constitutes defensible space. What had been taken to be defensible space in the flammable suburb or exurb model may not in fact be defensible under the conditions captured by flammable urbanism.

The novelty called for by this new fire system is actively being considered by the firefighting, planning, and emergency management communities (Thompson et al. 2018, CAL FIRE 2020b). Their progress is beyond our scope. We only point to this evolving situation to emphasize the importance of seeing fire; climate conditions; urban, suburban, exurban, or rural form; firefighting philosophy; and public expectations as part of a coproduced, social–ecological system. The dialectic of all these social and ecological phenomena together produces a highly entangled, complex system.

The emerging systems model for the novel catastrophic fires contains many components that act at new levels of intensity. It will be important to identify and purge components of interactions that are inappropriate holdovers from the other three fire-district systems models (table 1). As the world changes, it is not the use of a system model per se that is a problem. Rather, it is a problem if some parts of prior models are uncritically brought into the new systems model intended to cover the new catastrophic fires. An example of a holdover assumption is the expectation that fires in human settlements can and must be put out (Thompson et al. 2018). This is a tenet of the fireproof district model. Indeed, many features of the fireproof district model operationalize this principle. The model includes actions to reduce fire risk, changes in the materials used and the spatial arrangements within cities, and puts in place institutions and regulations to promote fireproofing.

An urban fire reporting model also emerged in the media associated with the fireproof district model. Here are its tenets, which are conspicuous even today in media reports of wildfire: Settled areas are not supposed to burn. If they do burn, someone has been negligent or criminal in action. The responsible agent must be identified. Restitution must be made (Smith 1992, White 2020). This reporting model may reinforce unrealistic expectations in the face of climate-driven, regional fires (Nilsson and Enander 2020), even if some ignitions or spread can be blamed on specific individuals or private infrastructure, such as sagging power transmission lines. A new fire model, perhaps similar in intent if not in content to our hypothetical flammable urbanism, would be useful in guiding public education, media approaches, new prevention and firefighting strategies, and novel regionally coordinated policies (Hewlett Foundation 2020). The role of systems thinking in the flexible, open-ended contemporary sense, can play a role in the societal response to the new catastrophic fire regimes emerging so widely around the world.

Conclusions: Using the systems concept to understand coproduced social–ecological interactions

The core of the contemporary systems view embodies ideas that are important to both social sciences and biophysical ecology. These include such things as focus on consequential interactions, the role of multiple influences, the agency or ability of various system components to respond to those influences, and the dynamism and open-endedness of the systems modeling process intended to represent specific situations or conditions. These core ideas are accessible to both social and biophysical researchers. This fundamental, core idea of the system supports the creation of diverse models that expose the great variety of differences among places, times, and circumstances in which consequential interactions must be understood (figure 1). When those models acknowledge and propose how social–ecological systems are coproduced, they can facilitate interdisciplinary interaction across the social and ecological spectrum.

We have used the contrasts in the predominant kinds of human–natural relationship exhibited by fires that burn in various parts of cities, suburbs, wildlands, and urbanized regions (table 1) to illustrate the utility of the flexible, contemporary systems approach. We have sketched key aspects of hypothetical systems models that might represent the different ways in which such processes as ignition, spread, impact, suppression, and cultural ideas of fire can be combined under different circumstances. It is not our intent to present a completely worked out systems theory of fire or fire change. Our hypothetical fire models are, rather, intended to illustrate how a social–ecological approach to systems models can capture the dynamism of the interactions among the social and ecological processes of cities, suburbs, exurbs, and wildlands. The massive changes in climate seem to be rearranging the processes and the interactions that limit or promote fire in the Anthropocene (Bowman et al. 2020, Goss et al. 2020, Duane et al. 2021, Pyne 2021).

The social tumult occasioned by catastrophic fires shows the kinds of practical problems that can result from the mismatch between particular systems models and changing reality. Practical fire management tactics can fail as the reality shifts beneath the cultural foundations set by previously useful fire models. Furthermore, the capacity of the public, the press, and decision-makers to adjust can be limited by holding to a fire model that was constructed to explain a fire regime that predominates under different circumstances.

Fire reporting models are especially problematic if they reflect cultural values that may have been established under a different fire regime (Smith 1992, Nilsson and Enander 2020). These can color the assumptions about feasibility of suppressing or fighting wildfire and, indeed, about the assignment of guilt when socially damaging or fatal fires start or cannot be extinguished. Although these models embody social values, they too can be discordant with the evolving reality of fire-triggered catastrophe. The assumption of defensible space is a practically important point of dissonance to which the models point.

There are undoubtedly other examples where understanding the social–ecological coproduction of systems can be used to prepare for, manage, and recover from disasters. Recalling that all disasters are, in fact, socially and naturally coproduced, it may be that appropriately scaled and focused system models can help society deal with new intensities and distributions of catastrophes now seen in the headlines. The specter of massive and frequent hurricanes, extreme and now more frequent river flooding, increasing coastal inundation, lengthening droughts, and intense inland storms will continue to challenge researchers, policymakers, managers, and the public especially when disasters occur in sequence (Machlis et al. 2022). With a shared understanding of the system idea, we expect that the social sciences and ecological sciences can become better partners in understanding coproduced systems and contributing to civic discourse in a time of extraordinary change.

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