

# An overview & synthesis of disaster resilience indices from a complexity perspective

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## ARTICLE INFO

### Keywords:

Complex adaptive systems  
Resilience  
Indicators  
Disaster index  
Urban systems  
Socio-ecological systems

## ABSTRACT

Identifying Disaster resilience indices (DRI) for cities and communities remains a common approach for assessing their structural ability and inherent capacity to cope with, recover from, and adapt to disasters. Particularly popular are composite DRI methodologies that are quantitative, top-down, and geographically mappable. DRI have become more comprehensive as the complexity of urban systems is increasingly acknowledged. However, DRI remain criticized as static, reductive, and inadequate when viewed under a complexity paradigm, which views urban systems as Complex Adaptive Systems (CAS), where observed properties (like resilience) emerge from many interactions among heterogeneous agents in a network. Literature reviews have covered the state and trends for DRI development. Our objective is to synthesize literature at the nexus of these reviews, CAS, and Socio-ecological Systems (SES) to determine the extent to which commonly adopted indicators relate to widely accepted tenets of CAS. Findings show that DRI indicators usually relate more closely to temporal snapshots of vulnerability, and alternative framings of current indicators along with interdisciplinary approaches could better capture CAS aspects of urban resilience. Research and development should strive to develop DRI based on underlying principles of CAS and SES, and consider adapting top-down quantitative approaches with thick data, network models, and mixed-method triangulations. Explicitly associating complexity theory with DRI can (i) help researchers in socio-technical and socio-ecological domains develop improved resilience indicators and assessment methods that are clearly differentiated from vulnerability metrics, and (ii) guide policy and decision-makers, amid future uncertainty, to better identify, implement and track capacity-enhancing measures.

## 1. Introduction

As society continues to evolve, interacting networks of people, objects, and systems within economic, technological, social, and ecological dimensions are becoming increasingly interdependent [1]. Urban systems, the interconnected combinations of infrastructure like power, water and waste systems, along with the social organization and institutions that altogether make up and govern an urban area like a city or region, are likewise interdependent, dynamic, and constantly evolving [2,3]. Complex Adaptive Systems (CAS) are characterized by interactive heterogeneous networks where a change in one component can affect changes in other components such that structures, processes, and organization emerge from their interactions (e.g., the ability of community to recover and adapt to future disasters arising from strong and weak social ties among diverse actors in response to a flood). Such emergent

phenomena include resilience, the structural flexibility to adapt and learn when the unforeseen happens. An urban system as a CAS is further characterized by being very difficult to predict or understand its inner workings by dissection of individual system components (i.e., the sum is greater than the parts). Theoretical perspectives of the urban space that embrace this view are becoming more widely recognized among resilience-related fields [4–7].

As the interrelationships among social, ecological, and technological systems (i.e., urban dimensions) are becoming recognized, disaster resilience index (DRI) methods are becoming increasingly comprehensive, yet are not necessarily based on CAS concepts (see sections 3–5). The variety of approaches and variables across urban dimensions suggests that index development faces overwhelming challenges and may be inadvertently substituting for an understanding of urban systems as CAS. While efforts to develop DRI aim to justify and guide resilience

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<https://doi.org/10.1016/j.ijdr.2021.102165>

Received 1 December 2020; Received in revised form 16 February 2021; Accepted 1 March 2021

Available online 3 March 2021

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investments, it has been argued that the complexity inherent in urban systems is not being captured by these methods [8,9]. If key complexity concepts are overlooked, and research and development of indices are misguided toward increasingly sophisticated but tangential methodologies, attempts to make communities resilient would be futile. In turn, adaptation efforts may not pay off and the case for investing in resilience may be undermined. Resulting interventions can either neglect or undermine resilience capacities, and unintended trade-offs can further compromise communities. Despite the popularity and practicality of DRI, the reduction of an urban system to a set of quantitative indicators runs the risk of sunken investments and maladaptation that can compromise the resilience of future cities [10,11].

Given the concurrent trends of growing recognition of complexity and the prominence of composite indices, an understanding of how current methodologies and variable selection fail to capture the complex properties of an urban system would result in more effective decision-making. Complexity-oriented development and application of resilience indices can provide a way to profile resilience capacities, augment DRI with complexity-related methods, and develop system-oriented enhancements (e.g., social connectivity) in dealing with future urban and climatic uncertainties. In order to enhance urban resilience to reduce human and economic losses in the face of climate change, socio-technological evolution, and a non-stationary future due to surprise events, it is imperative to provide city planners and managers a way of determining actionable yet pragmatic indicators, such as those that can be leveraged from data, in maps, engineering and decision models [12, 13].

## 2. Objectives and scope

Several publications provide literature reviews of the current landscape of resilience indicators, respective methodologies, and major concepts for composite index design (e.g., Refs. [14–16]). However, these works stem from disparate perspectives, and although complexity is sometimes mentioned, they do not systematically apply a CAS lens. Our overarching aim in this paper is twofold (Fig. 1): to first synthesize established literature on CAS and resilience of urban systems (sections 3–5), and secondly, to draw subsequent connections between commonly used DRI indicators and generally accepted properties or tenets of

resilience and CAS (sections 6–7). The specific objectives listed below are meant to aid researchers, planners, and decision-makers to acquire a different perspective into resilience of urban systems in terms of conceptualizing and integrating complexity into well-known tools (i.e., DRI):

- (i) Provide a background and synthesis of the literature at the nexus of disaster risk, urban systems, socio-ecological resilience, and complexity.
- (ii) Characterize major trends in indicator selection for composite index development based on a meta-review of established review articles that discuss indicator selection for multi-dimensional (i.e., social, institutional, infrastructure, etc.) composite disaster resilience indices (DRI).
- (iii) Outline the capabilities of DRI and respective indicators to capture properties of CAS, identify deficiencies in this regard, and discuss routes toward improving DRI from a complexity perspective.

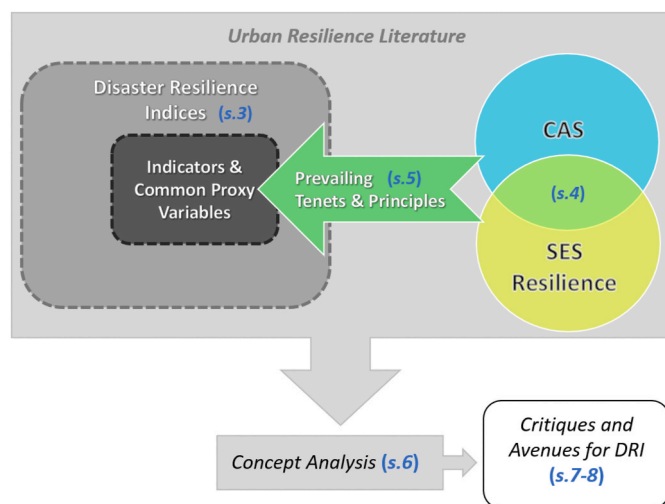
The analytical framework is first addressed via a brief meta-analysis of the literature on resilience indices (section 3), followed by contextualizing urban infrastructure and resilience in terms of CAS (section 4). Sections 5 and 6 describe how the objectives were explored through a selection of core DRI indicators in terms of common tenets of CAS and resilience principles. This is followed by a synthesis of findings (section 7), and concluding with a general discussion and recommendations for further work on DRI (section 8).

## 3. Review of common approaches for vulnerability and resilience indices

### 3.1. The case for disaster resilience indices (DRI)

The discourse on urban resilience has been largely driven by climate change and extreme weather, and the subsequent need to identify vulnerabilities, enhance preparedness, and develop adaptive strategies [17–19]. Many definitions exist, but in general resilience is the ability of systems to adequately anticipate, cope with, adapt, and learn from sudden shocks like climatic disasters (more detail on resilience in section 4). Strategies that reduce the complexity of the structure and processes of urban systems to objective metrics, such as DRI, are attractive to urban researchers and decision-makers to develop clear, actionable insights toward making the “business case” for resilience investments and tracking progress of these measures when implemented [20,21]. Indices are relatively simple sets of numerical metrics (e.g., a value of 0 indicating very little resilience, and 1 indicating very high resilience) or categorical metrics (e.g., low-highly resilient) that can be used to compare the relative resilience status of a place-based system (e.g., community, city, county, or state) over time, or to another system (e.g., Community Disaster Resilience Index by Texas A&M, see Peacock, [22]; and the City Resilience Index by Arup, see City Resilience Framework, [23]).

Comparative metrics and well-selected indicators (however normative) empower decision-makers to take action to implement research-oriented resilience plans, by clearly identifying strong and weak areas so that resources can be efficiently allocated [24]. Community resilience metrics can enable investments toward significant economic outcomes such as lower disaster costs), more stable local economies, and enable communities, governments, and the public sector to take capacity-building actions [20,25–28]. As is evident in programs like the late 100 Resilient Cities, DRI enable comparisons between cities and supports research and design toward learning from disasters, developing strategies, and transferring knowledge.



**Fig. 1.** Conceptual diagram illustrating the objectives, approach, and contribution of this paper towards identifying composite disaster resilience indices (DRI). Complex Adaptive Systems (CAS) and Socio-ecological Systems (SES) literature is reviewed to identify prevailing tenets and principles that can be used to conceptually analyze typical choices for resilience indicators and proxy variables. Numbers in blue correspond to which sections of the manuscript each component is covered (e.g., “s.3” means DRI are discussed in section 3).

### 3.2. Identifying an established core of DRI indicators

To identify a set of common types of indicators, a literature search for reviews of DRI and respective indicators was performed using combinations of the key terms (Fig. 2): resilience, metrics, indicators, measurement, composite, indicators, indices, disaster, climate, and review.<sup>1</sup> Google Scholar was used as the search engine because of its wide accessibility, links to articles hosted in multiple databases, and does not favor a particular group of publishing outlets [29]. Several articles published after 2015 cite previous reviews, so articles older than 2016 were excluded. Results were further filtered for peer-reviewed publications with at least a partial focus on quantitative indicators specific to resilience of urban systems to natural and general hazards, as opposed to vulnerability, risk, or resilience to other phenomena. Reviews considering only a single dimension of urban systems were excluded, such as those focusing only on the social domain or general social resilience. However, community resilience reviews were retained when they considered multiple dimensions of urban systems in respect to a community, such as infrastructure assets.

Table 1 lists the ten review articles that were ultimately selected, which summarize and evaluate the state of DRI using various approaches including bibliometric<sup>2</sup> and qualitative literature analysis [15, 30–32], case study compilation and analysis of existing index frameworks [14,15,20,33], and conceptual analyses of current research progress that includes DRI [9,34]. Syntheses from these reviews include highlighting theoretical perspectives, dominant dimensions of resilience (e.g., economic, institutional), and trends regarding methodological choices for DRI.

Regarding the overall capacities that resilience metrics should indicate, Beccari [15]; Cai et al. [30]; Cutter [20]; Parsons et al. [33],<sup>3</sup> and Sharifi [15] list some of the persistent indicators adopted across methodologies. The most widely cited of the selected articles, Cutter [20]

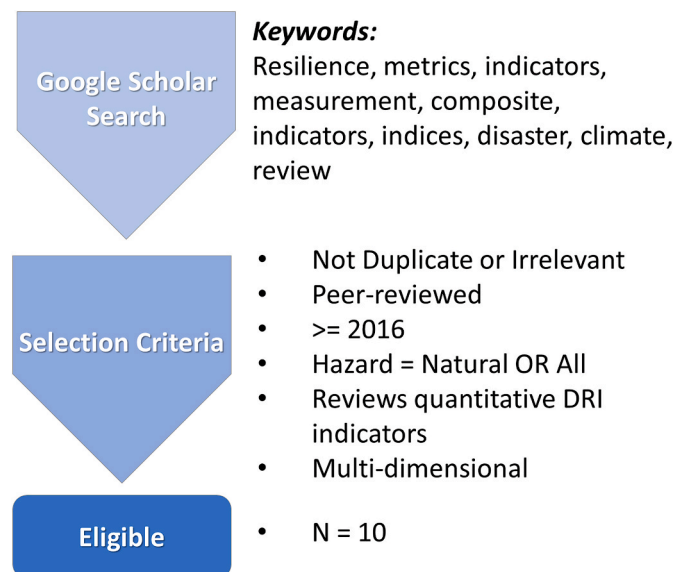


Fig. 2. Summary of the literature search method adopted to identify papers reviewing common and established DRI indicators.

<sup>1</sup> Keywords like “COVID-19” or “pandemic” were excluded because these events were still too recent and underdeveloped.

<sup>2</sup> Bibliometrics is the use of statistical methods to analyze books, articles and other publications.

<sup>3</sup> Presented as a list of indicators chosen for the Australian Natural Disaster Resilience Index based on a literature review.

**Table 1**

Selected articles that review literature and compilations of disaster resilience indicators and indices.

| Authors               | Description of the Type of Application and Index framework Proposed                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|-----------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Asadzadeh et al. [14] | <ul style="list-style-type: none"> <li>• No list of persistent concepts or variables compiled, but rather focuses on dimensions and methodological choices.</li> <li>• Proposed eight-step procedure for composite indicator building.</li> <li>• Recognizes increasing complexity in community resilience and distinguishes resilience in terms of socio-ecological and engineering perspectives.</li> </ul>                                                                                                                                                                            |
| Beccari [15]          | <ul style="list-style-type: none"> <li>• Comprehensive bibliometric review of vulnerability, resilience, risk composite indicator methods.</li> <li>• Includes list of dominant variables and concepts from the literature.</li> <li>• Concludes that deductive, quantitative and mappable methods are dominant.</li> </ul>                                                                                                                                                                                                                                                              |
| Cai et al. [30],      | <ul style="list-style-type: none"> <li>• Systematically analyzes 174 scholarly articles related to resilience measurement using content analysis and review tables in terms of definitions of resilience, approaches to resilience measurement, most commonly adopted indicators, and proposed adaptation strategies.</li> <li>• Tabulates most frequently used resilience indicators in rank order and by the top disaster types found in the systematic analysis.</li> </ul>                                                                                                           |
| Cariolet et al. [31]  | <ul style="list-style-type: none"> <li>• No list of common concepts but includes a detailed discussion of variable choices.</li> <li>• Critiques resilience indicator methods and composites as too simplistic and suggests hybrid methods to better capture complexity of resilience.</li> </ul>                                                                                                                                                                                                                                                                                        |
| Cutter [20]           | <ul style="list-style-type: none"> <li>• Evaluates 27 DRI and approaches in terms of theory, spatial characteristics, methods, and resilience domains (e.g., community, economic).</li> <li>• Concludes that there is no dominant framework but lists common core concepts, measurements, and prevailing proxy variables.</li> </ul>                                                                                                                                                                                                                                                     |
| Johansen et al. [34]  | <ul style="list-style-type: none"> <li>• Focused on social resilience, but does include multiple resilience dimensions.</li> <li>• Classifies metrics as community-based, sociological, or sector-specific, and reviews methodological choices between these three categories.</li> </ul>                                                                                                                                                                                                                                                                                                |
| Koliou et al. [9]     | <ul style="list-style-type: none"> <li>• Broad overview of the state of research on resilience dimensions across disciplines.</li> <li>• Reviews community resilience initiatives on international, national, regional, and local levels, including infrastructure domains and essential lifelines.</li> <li>• Calls for research regarding integration of system of systems, characterization of community-built environment, critical infrastructure interdependence, social complexity at multiple scales, and coupling engineering, economics, and social science models.</li> </ul> |
| Parsons et al. [33]   | <ul style="list-style-type: none"> <li>• Includes a brief survey of index landscape and presents framework, themes, and indicator selection for Australian Natural Disaster Resilience Index (ANDRI).</li> <li>• ANDRI synthesizes concepts and variables from the survey, with a greater focus on capacities and inclusion of less common variables such as learning.</li> </ul>                                                                                                                                                                                                        |
| Rus et al. [32]       | <ul style="list-style-type: none"> <li>• Reviews resilience and respective sub-components from complex urban system and seismic risk perspective across four dimensions: technical, organizational, social, and economic.</li> <li>• Integrates physical and social components of an urban system and highlights necessity to capture interactions (e.g., such as in a network or graph theoretical approach).</li> </ul>                                                                                                                                                                |
| Sharifi [15]          | <ul style="list-style-type: none"> <li>• Reviews 36 resilience frameworks in terms of resilience dimensions, scales, temporal dynamics, methods, and applications.</li> <li>• Concludes that ecological dimension is often under-represented and a comprehensive model that includes all resilience criteria is lacking.</li> </ul>                                                                                                                                                                                                                                                      |

presents a measurement core for disaster resilience with proxy variables that are commonly found in publicly available data based on a review of established indicators and methods, and categorizes them as assets or capacities for resilience (Table 2). This core largely aligns with the other review listing persistent indicator criteria (particularly Beccari [15], and

**Table 2**

Persistent variables for community disaster resilience (right column; as interpreted from Ref. [20]) based on assets (resources that can be leveraged upon disasters) and capacities (capabilities that emerge upon disasters) (left column).

| Domains and Capacities for Resilience Indicators | Common Types of Proxy Variables                                                |
|--------------------------------------------------|--------------------------------------------------------------------------------|
| Community assets and functions                   | Community services (number)                                                    |
| Connectivity                                     | Feeling of belonging to the community proximity to urban areas                 |
| Economic                                         | Income                                                                         |
| Emergency mgmt.                                  | Shelters, evacuation routes                                                    |
| Environmental                                    | Impervious surfaces                                                            |
| Infrastructure                                   | Buildings of various types (emergency, government, power, bridges, commercial) |
| Information/communication                        | Prior recovery, hazard severity                                                |
| Institutional                                    | Mitigation plans (% covered)                                                   |
| Social                                           | Educational attainment                                                         |
| Social Capital                                   | Civic organizations; religious                                                 |

Cai et al., [30]; though the latter does not include indicators in the environmental domain). Therefore, the following analysis leverages this core of indicator concepts and proxy variables for analysis against essential tenets of complexity and principles of SES. This set is not intended as an exhaustive list of concepts and indicators, but rather as a representative set to demonstrate how common approaches for resilience indicator selection aligns with fundamental CAS and SES resilience perspectives. However, indicators and proxy variables from the other reviews were sometimes noted for comparison or as additional examples.

### 3.3. General takeaways from the selected articles

While there are only partial overlaps between reviews in Table 1 due to varying scope, methodology, and framings, there is agreement among certain critiques and conclusions. Generally, quantitative top-down methods (e.g., relying on aggregate datasets rather than field data) are tremendously popular, especially if amenable to geographic visualization (e.g., DRI-enabled decision tools like GeoApps). Indicators can be classified into two general domains of resilience, (i) assets or capital, and (ii) capacities and governance. Holistic indices that aim to be hazard-agnostic suffer generalization and contextual limitations. Validation (i.e., internal and external validation, cross-validation, uncertainty and sensitivity analysis, ground truthing) remains a persistent problem and is sometimes entirely ignored in indicator frameworks. The prominence of insufficient validation and uncertainty analysis and their importance has been noted for social vulnerability indices (SVI) and DRI, with suggestions that leverage statistical methods (e.g., using “revealed vulnerability” data like human loss or satisfaction with damage compensation) and cross-validation with alternative studies [29,35]. Lastly, interactions between urban system components and subsystems remain a necessary but difficult area for research, development, and coupled methods or interdisciplinary pursuits.

## 4. Contextualizing CAS and urban resilience

“The complexity turn”<sup>4</sup> has influenced several research fields interested in urban resilience to climatic disasters, such as disaster risk reduction, urban geography, and resilience engineering and management, into framing cities as complex systems [5,7,16,20,36–38]. Seminal publications paving the way for this turn stem from ecology, particularly the resilience of ecological systems framework by Holling [39,40]. Ecological perspectives view CAS as composed of holons (hierarchical levels or subsystems with subjective boundaries where

information and materials are gated and transferred [41]; that are nested in a panarchy (holons exist as hierarchical series of adaptive cycles, and both top-down and bottom-up controls between holons drive resilience and evolution) [42]. Resilience is framed as an emergent property of CAS, which as an interconnected whole, can absorb change, reorganize, or transform while maintaining major functions and an essential identity [43].

Resilience as coping with change and perturbations has since been adapted into engineering for critical infrastructure systems (CIS) services [16,44–46], and research on the built environment as SES and socio-technical systems (STS) [47–50]. In terms of seismic community resilience, Bruneau et al. [51] present four key properties of resilience in both physical and social systems (“4 R’s” of resilience): Robustness (i.e., strength or hardness against degradation or function loss), redundancy (extent of substitutable elements or systems), resourcefulness (capacity for identifying problems, prioritizing, and mobilizing resources), and rapidity (timeliness in meeting goals after disruption) [16]. Proposed five main sub-attributes from a techno-centric viewpoint: (i) Preparedness, the ability to anticipate and proactively invest in adaptation strategies; (ii) Robustness, or the ability to withstand sudden shocks and provide the service it has been designed for; (iii) restructurability, or the flexibility to reorganize so as to maintain at least partial functioning; (iv) restorativity (rebounding), the ability to recover functions in a timely manner and without excessive losses; and (v) adaptivity, the ability to learn from failure and adversity and to incorporate changes that improve the ability of systems to handle similar events in the future.

Some engineering-oriented attributes, like robustness, are conceptually the inverse of vulnerability (sensitivity to damage or loss upon exposure). While it is reasonable to view robustness as a component of resilience, this paper aims to distinguish attributes of resilience from vulnerability, taking on the perspective that urban systems are always vulnerable in some form, so it is salient to focus on attributes that relate to the flexibility, agility, and persistence of a CAS. Resilience centered on flexibility and CAS capacities better align with CIS as panarchies in terms of vulnerability paths and “creative destruction” [52], and with STS perspectives that put transformation at the core of resilience of human-technological systems [53]. In this way, urban systems are like ecological systems that display complex interconnections and nested cycles of evolutionary adaptation [54,55].

SES perspectives traditionally leverage complexity-driven concepts and frameworks like adaptive cycles for ecosystems and society as interconnected subsystems, but theoretical frameworks have extended them to the built environment and urban resilience. Principles of resilience for ecosystem services have been proposed which include diversity, redundancy, connectivity, polycentricity, slow variables and feedbacks, understanding of CAS, learning and participation (Table 3; [56–59]). SES perspectives that include coupled infrastructure have proposed partially overlapping principles that more directly acknowledge the built environment (e.g., Refs. [47,60]). Such principles highlight systemic properties that can be monitored, measured, and leveraged to enhance resilience of urban systems. These perspectives highlight CAS properties that enable resilience, while linking urban infrastructure to social dynamics, ecological interactions, and technological evolution entangled in a complex system. Therefore, these SES resilience principles represent key concepts for CAS (section 5), and are the basis of our analysis in section 6.

The coupling of multiple complex and heterogeneous systems has greatly compounded the complexity in urban systems, making resilience to disasters difficult to measure, manage, and predict. Challenges have been noted, including those highlighting deep uncertainty (where probabilities of possible futures are too difficult or impossible to rank) and wicked complexity that requires fundamentally new approaches to how we function ([36,61–64]). Part of this wickedness and uncertainty has to do with infrastructure as embedded in rapidly coevolving technological and social systems in the Anthropocene, the geological age when humans dominantly drive the Earth system and accelerating

<sup>4</sup> The recognition of complexity as inherent and unavoidable in human and other systems.



**Table 3**

Resilience principles for complex systems from the socio-ecological perspective (based on [56–59]).

| Resilience Principle         | Description                                                                                                                                                                                                                                                                                                                       |
|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Connectivity                 | The extent to which paths and degrees are present for resource and information flows and interactions across socio-ecological landscapes.                                                                                                                                                                                         |
| Diversity & Redundancy       | Diversity refers to the variety of elements, balance in the quantities of each element, disparity between elements, and heterogeneous distribution. Redundancy refers to the replication of elements or functions in a system that can ensure that some elements compensate for the loss of others (i.e., opposite of disparity). |
| Learning and Experimentation | The processes of developing knowledge, behaviors, skills, values, and preferences at individual, group, and societal levels within an SES.                                                                                                                                                                                        |
| Participation                | Active engagement of relevant stakeholders in the governance and management of SES.                                                                                                                                                                                                                                               |
| Polycentricity               | A governance system composed of multiple centers of decision making nested at different scales.                                                                                                                                                                                                                                   |
| Slow Variables & Feedbacks   | Variables with slow rates of change as to often be considered constant, but has the potential for feedback and the surpassing of critical thresholds.                                                                                                                                                                             |
| Understanding of CAS         | A mental model or cognitive framework characterized by the acknowledgement of unpredictability, emergent macroscale behaviors, continuous evolution, responsive adaptation, and uncertainty pervasive in SES.                                                                                                                     |

change drives high levels of unpredictability [36,48,61]. The challenge for disaster resilience and established DRI is merging what was traditionally thought of as natural disasters into what is now being conceptualized as a highly interconnected and unpredictable, yet human-driven Earth system.

Anthropocene perspectives increasingly underscore the irreducible complexity of social dynamics. Human agency, conscience, and societal values, along with technological dominance, introduce subjective interactions into coupled systems that effect how these CAS self-organize. Human cognition, relative to technical and ecological systems, makes coupled systems asymmetrical – that is, dominated by the social domain where collective choices and sociopolitical forces govern how urban systems adapt [145][65]. [66] argue for the complexities of sociopolitical infrastructure such as formal and informal rules are necessary for urban resilience thinking. The call for the inclusion of highly complex social dynamics also characterizes how urban resilience is being conceptualized, and forms the basis of criticism by some social scientists that DRI are too-reductive, normative, context-dependent, and static [8, 67].

## 5. Resilience principles and the tenets of CAS

### 5.1. Finding a core set of essential CAS and resilience attributes

As efforts to frame urban resilience are converging around CAS, traditional approaches for understanding urban systems and preparing for the future are inadequate, and a turn toward systems thinking is necessary [57,68–72]. There are many branches in the history of the complexity sciences that evolved in parallel and sometimes interlink (e. g., general systems theory, cybernetics), so an exhaustive treatment of this history is beyond the scope of this paper.<sup>5</sup> However, there are some commonly accepted essential tenets of CAS. In a recent review of complexity theory, Turner and Baker [73] outline the many definitions of CAS and respective characteristics, and propose a set of “tenets” of CAS (Table 4.).

Some tenets are closely related or interdependent allowing them to be bundled together. For instance, since path dependence was explained

**Table 4**

The link proposed in this paper between important tenets of complex adaptive systems (CAS) and different characteristics of socio-ecological systems (SES) resilience.

| CAS Tenets                       | Description                                                                                                                                                                                                                                                                                                                                                                                    | Most Closely Related Resilience Principle |
|----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|
| Adaptivity                       | Systems respond to and affect external environments and reconfigure to meet changing demands (i.e., systems adapt and evolve).                                                                                                                                                                                                                                                                 | Diversity & Redundancy                    |
| Emergence                        | Synergistic outcomes from the interactions of several heterogenous components that spontaneously interact to form patterns (i.e., <i>self-organize</i> ) that cannot be deduced by dissecting attributes of any one individual component (i.e., “The whole is greater than the sum of the parts”).                                                                                             | Connectivity, Polycentricity              |
| Irreducibility                   | Characterized by inherently partial system framings (i.e., “Whole system ignorance”), uncertainty and unpredictability of system outcomes.                                                                                                                                                                                                                                                     | Understanding of CAS, Participation       |
| Operates between Order and Chaos | Systems can experience spontaneous self-organization and emergent order (i.e., innovation and new structures emerge at “at the edge of chaos”).                                                                                                                                                                                                                                                | Learning & Experimentation                |
| System History                   | Systems have <i>non-linear</i> relationships among variables in time, and future conditions are <i>path-dependent</i> (i.e., limited by previous paths and conditions). Systems exhibit a <i>sensitivity to initial conditions</i> so that small differences can produce widely different outcomes and dynamics over time, while slow variables can unexpectedly approach critical thresholds. | Slow variables & feedbacks                |

in terms of sensitivity to initial system conditions or history, the three tenets are consolidated into “sensitivity to initial conditions”. Other systems characteristics describing the essential tenets can be similarly handled. For example, uncertainty in complex systems was incorporated into the property of irreducibility because any system representation is necessarily a limited and biased manifestation of the “actual” system so that subsequent indicators involving “uncertainty” in some manner [74, 75].

Resilience emerges from systemic interactions occurring before, during, and after disturbances, where the tenets of CAS and SES resilience principles come into play to support adaptation, learning, and the “bouncing back” of urban systems. For example, connectivity and polycentricity can facilitate the ability for an urban CAS to self-organize; diversity and redundancy enable adaptivity; slow variables and feedbacks are linked to non-linear patterns and the history of the system; the irreducibility of CAS require an understanding of CAS and participation; learning and experimentation speak to the possibility of re-ordering after unforeseen consequences [4,76,77].

It is important to note that many CAS discussions arise out of non-agent or socially agnostic systems, and in-turn, downplay or overlook the role of human elements (e.g., institutional structure, leadership). Equity, for one, is the most difficult resilience principle to relate to the tenets as it is normally based on a call for justice (i.e., resilience for whom). That equity relates to irreducibility and systems thinking is here justified in terms of the “5 W’s” of resilience (resilience for what, whom, where, why and when), which stifle the framing of an urban system as generally resilient without potential trade-offs or winners and losers [7, 78,79]. Equity is further related to irreducibility and systems thinking in

<sup>5</sup> See Ref. [37] for an exceptional review on the historical evolution of the complexity sciences.

terms of Edwards' [80] four "E's" of resilience which highlight the limited role of centralized planning or definitive templates for building resilience in the social domain: Engagement (strategies based on dialogue and feedback), education (as embedded in daily lives in any form), empowerment (assumes communities have relevant experience and should be given tools and resources to act), and encouragement (communities are encouraged to play a role by both formal and informal institutions).

In this way, CAS tenets and SES resilience principles can be distinct, yet related. This paper does not view these tenets and principles as absolute and universal, but rather as the outcome of a synthesis of how Anthropocene challenges like urban resilience to more frequent and intense climatic shocks are being framed. We adopt the CAS tenets and SES resilience principles in our analysis in section 6 to guide reflections on common types of resilience indicators, and DRI applications. However, it is important to note that the nature of urban resilience as a CAS presents major limitations and assumptions that challenge the generalization and application of DRI [32].

### 5.2. Potential misalignments between established DRI and CAS

While index methods aim to reduce urban resilience to a set of capitals and capacities for an overall measurement of resilience, CAS research tends to focus on unearthing the dynamics and spatiotemporal patterns within a system that lead to the emergence of resilience. Common examples are process-oriented and multi-agent models where networked agents or components interact to produce macro-level trends or transitions in state variables [81–83]. Such models are meant to map the dynamics of systems and can indicate the potential for a system to self-organize and adapt to perturbations. Metrics associated with these approaches are often topological or pertain to the potential for interaction, such as the number of links that connect to a given node (degree of a node), or network density, the ratio between the number of connections to the number of possible connections [84]. In terms of resilience, computational models seek to determine points of criticality where interactions tip the system toward transitioning to a different state that can be either desired or undesired [82,84]. Macro-level metrics are sometimes sought, such as a high-level metric for self-organization of a CAS by King & Peterson [85].

It is important to point out that composite indices may be categorically misaligned with CAS theory due to their common framing of resilience as representable by a sum of quantified parts, whereas complexity assumes synergistic effects between many autonomous interacting parts, which can be unpredictable or novel. Composite index methodologies implicitly assume a "simple" system in that a selection of quantifiable subsystems corresponds meaningfully to how urban systems behave upon disasters. This misalignment occurs methodologically when indicators are added up and assumed to indicate some ordinal level of resilience, but also conceptually when variables are assumed to be meaningful, consistent, and generalizable from one event to another, and among different and continuously evolving urban systems.

Approaches and epistemological assumptions between DRI and CAS-oriented methods may be fundamentally different, but they can still be viewed as either complementary to each other, or as a way to transition between dynamic models and linear indicator approaches [30,86]. The development of sophisticated modeling of CAS can be time and resource intensive (e.g., data, modeling experts), but have been used for scenario-testing, dynamic resilience metrics, and organizational learning [86,87]. Indices, however, offer a clear measure and more straightforward insights pertaining to variables and resources relevant to planners and stakeholders [24,88]. We recognize that the manner in which resilient performance of CAS are normally evaluated/quantified differ significantly from how index approaches measure resilience. However, to bridge the gap between these approaches this paper will focus on how concepts and metrics used for indices broadly relate to tenets of CAS and SES resilience.

## 6. Approach for conceptual analysis of resilience indicators from a complexity perspective

We have adopted CAS tenets and SES resilience principles to analyze the concepts and proxy variables (i.e., resilience assets and capacities) that are dominant in DRI (as shown in Tables 1 and 2). This was done by framing a set of guiding questions. For example, to relate the common disaster resilience concepts and indicators to the self-organization and emergence tenets, guiding questions include:

- Does the indicator capture connectivity in terms of the ability to self-organize?
- How is governance in terms of the ability to make decisions at multiple scales captured (i.e., polycentricity)?

While the range of methodologies is not discussed in detail in this paper, general implications of applying different methodologies are presented when relevant to a particular complexity tenet and resilience principle (e.g., choosing additive assumptions versus multiplicative or exploring more advanced techniques for a given indicator). Discussion points were developed for CAS tenets and SES resilience principles in terms of each of the common core of resilience indicators in section 3.2, including short descriptions of potential CAS significance, links to other CAS properties, and counterexamples illustrating how an indicator may be somewhat myopic in terms of complexity. Once completed, results were reviewed for general trends, significant findings, and holistic insights that may otherwise not have been captured by the piece-wise analysis. These results are described in section 7, followed by a broader discussion that incorporates insights from the reviewed literature (section 8).

## 7. Synthesis of Findings from Analysis of Core Resilience Indicators, SES Principles, and CAS Tenets

Of the indicators analyzed, social capital (bonds that communities can leverage for recovery upon disasters; Aldrich [89], and connectivity (linkages within and between systems; Turner and Baker [73], emerged as the most aligned with CAS and resilience of SES principles. However, indicators for the emergence of social capital are subject to contextual system histories (e.g., meanings or tipping points that vary from place to place), intricate trade-offs, and uncertainty toward generalizations amid evolving SES [90,91]. In terms of connectivity, social capital proxied by the number of civic or religious organizations and adherents as indicators suggests these kinds of institutions as nodal points where individuals and communities can connect and organize to redistribute resources toward coping and recovering from a disaster.

The focus on density for all types of indicators (i.e., units per administrative boundary) can indicate the order of potentially interacting parts or the potential for functional redundancy, the latter often cited in Table 1 reviews as a driving concept for indicator selection. However, focusing on proportions of a given variable tends to leave out modularity (the attribute of having components or groups of rules that act as "building blocks" that can be situationally recombined; Holland [45], and diversity (variety, balance, and disparity among elements; Biggs et al., [56]. While modularity may be more elusive to capture with straightforward indicators, diversity can be incorporated by methodologically shifting to data attributes that pertain to the number of different types and functions, rather than density of discrete units (e.g., number of types of religious centers, or religious pluralism rather than number of religious centers).

Ultimately, each indicator in our analysis could be critiqued for not meaningfully capturing complexity tenets in some way. This is to be expected due to the intent of resilience indicators as a reduced form or snapshot of system conditions, especially when viewed in a piece-wise fashion. Ecological and environmental factors are largely absent, which may be because such indices are normally integrated with

exposure metrics, models, and tools that capture topographical, hydrological, and climatic factors. Several indicators align with complexity tenets once reframed or considered as coupled with supplementary methods.

Results describing DRI indicators according to each complexity tenet and linked SESs resilience principles (subsections) are below. Selected examples are discussed, and relatively simple modifications for better alignment with tenets and principles are noted. Higher level critiques and suggested improvements for DRI (e.g., research, development, application) are discussed in section 8.

### 7.1. System history – non-linearity, slow variables, and feedbacks

Some common indicators can be framed as capturing system histories, including climate mitigation, impervious surface coverage (ISC), and previous exposure to climate hazards. Climate mitigation acknowledges emissions as a slow variable that contributes to the frequency and intensity of future potential disasters. ISC can be an insidious slow variable in terms of urbanization and urban flooding [92–94]. More directly, system history is captured as previous exposure to and severity of past disasters (e.g., number of presidential disaster declarations). Places that have been resilient after a disaster likely have developed human infrastructure (i.e., experience and knowledge) and lines of information and communication capacities that can support recover and reorganization. However, a central idea of resilience is that surprise events challenge established knowledge systems and infrastructure [95]. Nonetheless, previous disaster experience and hazard probabilities, especially if increasing in intensity and frequency through time, could indicate a greater likelihood to develop adaptive systems and prepare for the unexpected.

System history displays a minor presence in top-down composite methods. It is difficult to define, operationalize and measure slow variables and feedbacks within and between common indicators in a way that can be generalized from case to case. The potential for contextual effects can undermine basic assumptions for some indicators that assume like histories and tipping points across places. For instance, access is assumed for quantities of hospitals and disaster-relevant buildings. Considering insurance coverage and transportation connectivity as coupled with health units like hospitals may help indicate how accessible such units may be from a social and infrastructural perspective. Path dependencies and lock-ins built into communities and coupled infrastructure systems can have an impact on how effective implementations based on such indicators may be to either disasters or coming changes [96,97]. For instance, a place may have many emergency buildings that are vulnerable due to construction age and low investment in maintenance. Such interdependencies between indicators are often stressed as a next step for DRI in the literature reviewed (Table 1).

Quantitatively, slow variables can be captured as rates, limits, and thresholds (i.e., tipping points) of common indicators. Rather than proportion, the rate of development using a series of ISC data can indicate the approach to critical thresholds of development that outpace adaptation and coming environmental changes. Likewise, median income as a proxy for economic assets assumes incrementally additive units that contribute to resilience, whereas the percent below poverty assumes a quantitative leap in critical capacities, access, and vulnerabilities in the face of a disaster.

### 7.2. Emergence – self-organization, connectivity, and polycentricity

It is difficult to explicitly link emergence to index approaches in light of the misalignments outlined in section 3, but indicators like the number of religious organizations framed as a proxy for the kinds of social capital that can emerge amidst disasters shows an attempt to capture the potential for desirable emergent phenomena. As related to the emergence of adaptive qualities and resilience, connectivity and

organizational capacity are presented several times in reviews and index frameworks as concepts for variable selection. Connectivity indicators are usually linked to institutional/organizational assets and capacities (e.g., percent of religious adherents), or in infrastructural terms like communications (e.g., mobile or telephone access). The number of community, civic, or religious centers can be taken as a proxy for connectivity and the ability of a community to self-organize as churches and other religious centers often serve the public in need and can offer shelter, hope to recover, and guidance [98]. Non-profits and locally run community services may indicate social capacity for self-organizing to provide functions that are either unexpected, untrusted, or absent from other publicly provided sources [99,100].

Social capital is a driving concept for community resilience where indicators are used to queue for the social resources and linkages that emerge upon disasters. Volunteerism, place attachment, and civic engagement are some of the most common examples of indicators, and are captured with variables like percent of lifetime residents, proportion of voter participation, and quantities of civic engagement organizations. Community bonds, a feeling of belonging to a community, or being connected to urban infrastructure and institutions are commonly used criteria for connectivity. Other indicators of connectivity are framed around benefits of urban density, such as the proximity to critical urban services.

In terms of polycentricity, it is not clear that decision-making at multiple scales is present in the way resilience capacities are currently framed. However, since mitigation plans and activities may have implications at local, state, national, and international levels, the climate-related mitigation indicator at the community or municipal levels assume that taking part in mitigation activities along with other communities will make a difference at larger scales (i.e., local to global drivers). While the number of political districts within the spatial unit of analysis has been previously seen as political fragmentation [101], this indicator can alternatively be framed as polycentricity where spatially-derived metrics can proxy multiple levels of decision making relative to a population or area. Using currently established indicators, spatially relating community service nodes with higher-scale disaster centers or emergency services may indicate cross-scale connectivity and polycentricity. Granted, assumptions of cooperation versus antagonism and competition may be difficult to overcome.

### 7.3. Irreducible – understanding of CAS, participation and equity

Given that composite index schemes inherently reduce a complex situation into an operable numerical representation [102], oversimplification and uncertainty are inherent risks. Green infrastructure (GI) can indicate multifunctional infrastructure and ISC mitigation, but GI distribution may affect equitable access to green space and related benefits, or paradoxically induce gentrification [103]. Where GI can promote resilience in one place, it can create vulnerabilities in another.

Similar is true for indicators for social capital, a “Janus-faced” concept [91]. It has been found that low income communities with high rates of second-language households (two common indicators for vulnerability and low resilience), can leverage other forms social capital and even outpace wealthier communities for recovery [104]. In some cases, communities tied together by a common religious organization or other common identities like race and political affiliation may exclude a minority that is left vulnerable or purposefully put in a precarious state [105].

Many reducibility issues have to do with relationships between variables that depend on space and place. A persistent issue is the effect of different units of spatial aggregation (e.g., Census tract versus county or municipalities) on how patterns emerge (i.e., the modifiable areal unit problem, Simpson’s paradox). For instance, an area with a high DRI may have within it several pockets of very low DRI values that are obscured upon aggregation. In such cases, the uncertainty that arises from the choice of analytical scale is greater for generalized resilience

indices and those developed for specific planning circumstances [35]. Most index methods also assume that collections of indicators and their relationships can be generalized across geographies, such as Census tracts across a state. However, it has been shown that relationships and processes between the same set of DRI variables can differ from place to place [106,107]. Indicators also assume consistent relationships over time. Prior hazard experience assumes preparedness to known disasters. With a changing climate, disasters of unforeseen magnitudes or even types may challenge urban systems that have been resilient in the past. Infrastructure and buildings designed based on risk assessments and robustness to predicted events do not account for such an uncertain future [108]. Mitigation plans are common proxies for disaster knowledge and resilience, but the presence of adaptive management plans may be a potential variable that can indicate CAS understanding.

#### 7.4. Adaptivity – diversity and redundancy

Several DRI indicators reflect redundancy. Examples tend toward infrastructure redundancy with indicators like the number of emergency response units (e.g., fire, police, shelters), and density of principal arterial road miles (alternative evacuation routes). Indicators tend to represent some form of capital that can absorb impacts such as economic assets (e.g., median income), rather than capacities for restructuring and adaptation like modularity or diversity. Methodological frameworks largely rely on quantities per spatial unit (e.g., city, county, tract), so it follows that many indicators can be deemed a measure of redundancy for that particular asset, or overall information, infrastructural, or organizational capacities.

A few indicators can be interpreted as capturing a degree of diversity such as the proportion employed in the primary industry or the ratio of large to small business. The latter, for instance, can potentially suggest that a large proportion of small businesses means innovation and a diversity of competitors. Redundancy and diversity of production sources, employment opportunities, and multi-skilled workers can offer functional alternatives if industries and sectors are disrupted for relatively long periods of time. Current indicators can be extended to income diversity in terms of economic markets, such as the number of active economic sectors or markets, or the percent employed across industries.

Some indicators can capture diversity or modularity if conceptually reframed and relatively simple methodological modifications are made. The number of emergency response buildings (e.g., fire, police, shelters) can be interpreted as diversity if reframed as a metric based on how many different types of functions or building types are present. Specific measures of diversity like the Gibbs-Martin or Shannon Diversity indices can be used to indicate social diversity, or the diversity of resources, employment sectors, skillsets, and industries [60,109,110].

#### 7.5. Operating between order and chaos – learning & experimentation

Indicators relating to learning and experimentation include prior experience with hazards (e.g., number of disaster declarations or hazardous events), presence of adaptation and mitigation plans, and innovation (e.g., percent population employed in creative class occupations). It is assumed that prior experience with hazards proxies having learned and established improved information and communication capacities. Highly impactful disasters can materialize the unpredictability of climate events and performance of infrastructure and resilience mechanisms to a community. However, the subsequent response does not necessarily embrace safe-to-fail practices that more explicitly recognize the potential for future failures and unexpected conditions [61,68,111].

Resilience enhancements may be approached by investing in strengthening current systems and strategies, or by resilience thinking where more flexible and innovative systems are the focus. It is unclear if prior experience and emergency management allows for innovation and evolution toward novel and more resilient systems rather than recovering traditional and/or otherwise still vulnerable systems. An

appropriate balance between robustness and flexible systems that assume unpredictability are also not described by the presence of mitigation plans/spending alone. Further, mitigation and resilience efforts facing excessively rigid institutional structures can incur maladaptive qualities like lack of organizational flexibility and innovation [112].

While organizational capacities like learning and coping with complexity are being recognized [113,114], it is generally difficult to find clear indicators that proxy these capacities in terms of urban resilience to climate disasters. However, indicators like the presence of adaptation and mitigation plans can be extended to the number of editions of hazard plans or adaptive management plans that suggest experimentation and rethinking of past strategies. Urban density and proximity to urban cores can provide prospects for potential indicators such as those based on knowledge spillovers, the creative economy, and innovation hubs [115–117].

## 8. Discussion

An effective index should focus on a well-selected set of key variables that indicate changes in urban system in respect to resilience [32]. Considering the DRI review literature summarized in Table 1, it appears that in an attempt to better incorporate the complexity of urban systems, DRI approaches have annexed dimensions of urban systems (e.g., ecological, institutional) such that complexity is applied in terms of many components in many domains (e.g., social plus ecological plus infrastructure, etc.; We recognize the importance of acknowledging salient variables in all these dimensions). Such a perspective leads the process of index development to become increasingly complicated with evermore quantities of concepts and variables while overlooking critical systemic variables and dynamics (e.g. Ref. [41], lists 66 resilience concepts originally considered for the New Zealand Resilience Index). Complexity is about more than just having many different kinds of parts, as discussed in sections 3–5, and excessive variables can add statistical uncertainty and bias (e.g., implicit weighting via correlated indicators; Fekete [29], and make validation of DRI more difficult. Avenues for improving on established research frameworks (8.1), DRI development and application (8.2), and broader implications (8.3) are discussed below.

### 8.1. Avenues for further DRI research toward resilience indices

For researchers focusing on community resilience assessment, it is important to continue distinguishing resilience from risk and vulnerability [148], and determining how each concept applies to developing indices. Resilience remains often applied as “anti-vulnerability”, with some indicators essentially adapted as the inverse of established vulnerability indicators (e.g., Refs. [101,118]). Asset-oriented indicators like income or environmentally exposed structures like mobile homes speak more to sensitivity and exposure as factors for vulnerability [31, 79,119]. This can be problematic since it has been shown that a community can be both vulnerable to disruption yet bounce back quickly (e.g. Ref. [104]), and resilience as the capacity to reorganize and restructure after a disturbance can be missed. In complexity-oriented resilience research, however, vulnerability is viewed as an integral part or even precondition for resilience (e.g., Refs. [68,119,120]). A resilience index is less useful if it becomes a more comprehensive version of a vulnerability index, with an acknowledgement of complexity via additional dimensions for indicators. For composite resilience metrics, perhaps it is more useful a concept when framed as the capacity for reorganization after a disturbance.

Illuminating how more elusive qualities like polycentricity and self-organization can be proxied by relatively straightforward indicators is relevant for resilience researchers. In their article on disaster resilience and CAS theory, Coetzee and colleagues (2016) concluded that using CAS concepts (such as those in this paper) would enable disaster researchers to, “... analyze the dynamic changes in societal resilience



profiles.” There are three implications for DRI here: (1) profiling cities or communities according to CAS concepts, (2) profiling communities systematically over time to observe adaptive capacity as an ongoing dynamic, and (3) profiling the relative complexity of infrastructure, community, and organizational response of urban systems. The third item relates to autopoiesis (the self-producing capacity of CAS in terms of organization and information) and Ashby’s Law of Requisite Variety (control systems must match the complexity of their environment), where autopoiesis is measured as the system’s complexity divided by the complexity of its environment (Ashby, [121]; Gershenson, [2]; see Zhang et al. [122] for an example framed around information entropy of an urban ecosystem). A complexity approach to resilience metrics would be more focused on governance, interconnections, and capacities, but critical forms of capital are still an essential component as critical stocks for adaptive efforts. CAS and SES principles already provide a framework to conceptualize systemic resilience indicators for an evolving complex urban system, when indices are viewed as an on-going process. Further, these principles can drive a rethinking of quantitative assumptions used for index building, such as thresholds for indicators where the proximity to critical limits can transition an urban system or its subcomponents into resilience-hindering or undesirable states [123].

Two relevant areas of interdisciplinary research include adapting DRI frameworks with network-based methods, or with transdisciplinary methods that rely on multiple ways of knowing. Kammouh et al. [124] developed a resilience index for a transportation network using Dynamic Bayesian Network (DBN) techniques that enable time-dependent relationships between indicators. Bozza et al. [125] propose a Hybrid Physical-Social Network model (HPSN) that incorporates a vulnerability index within a built environment network at the neighborhood level that includes buildings and roads exposed to a natural disaster. Modeling cities at different scales with such methods can illustrate how resilience emerges when components of an urban system are made vulnerable at different levels of criticality. Complexity science for cities suggests urban systems have consistent systemic properties as they grow and are subjected to perturbations, so there may be opportunities to observe CAS tenets and resilience principles and develop metrics supported by computational methods [115,126,127]. Alternatively, coupling indices with ethnographic and other qualitative methods can illustrate how indicators and CAS concepts manifest in the experiences of community members, which can either confirm, deny, or add nuance to quantitative assumptions.

It is possible to experiment with indicators that more closely relate to CAS principles and systemic, process-oriented perspectives. Suarez et al. [60] propose an indicator set for assessing socio-ecological resilience in cities that overlap with many of the concepts of this paper, which can offer a fulcrum for research and development toward a CAS-oriented index. Geographically sophisticated approaches like multi-scale geographic regression (MGWR) assume that a set of indicators has place-dependent processes. Yoon et al. [107] used MGWR to develop a Climate Disaster Resilience Index (CDRI) and showed how established resilience indicators have different relationships in different parts of South Korea. Such methods relate to system histories and irreducibility in spatial terms. Places have a unique history, meanings, initial conditions, boundaries, and interconnections. Therefore, it is important for DRI to be amenable to continuous evaluation, revision, and adaptation to specific applications.

## 8.2. Toward complexity-driven development & application of DRI

Co-production of DRI among research and practice, can support learning as a resilience principle, close the gap between top-down methods and on-the-ground realities (i.e., irreducibility of urban systems), and contextual adaptations of DRI (CITE). Community participation and engagement among and between communities, researchers, stakeholders, and decision makers is important toward ensuring that both the index methodology and the resulting resilience enhancing

measures are not myopic, unrealistic, or likely to cause injustice and conflict. Participation can facilitate context adapted DRI by qualifying the applicability of generalized indicators, identifying essential drivers for resilience and specific slow (i.e., control) variables that reach critical limits for a given city’s systems, and modify methodologies accordingly. In terms of the process of index development, Beccari [15] and Asadzadeh [14] discuss whether and how index methods incorporate participation for monitoring of results and adjustment of indicators, which can serve as a learning and experimentation process.

The need for adaptive methodologies is a cue for researchers and developers of indices toward algorithmic or modular methods that support participation, experimentation, and better align with an understanding of CAS. A simple example is an established SVI framework that was adapted with an alternative aggregation scheme and integrated into an interactive web-tool that decomposes indicators, made possible by collaboration with decisionmakers for the City of Knoxville, TN [128–131]. Van der Merwe et al. [132] developed and implemented a formative resilience assessment that leverages the seven SES resilience principles adopted here toward an on-going collective evaluation of resilience of an energy system. Formative assessments differ distinctly from top-down composite resilience indices (known as summative assessments), but such methods can be adapted along with composite methods for more holistic and robust outcomes, incorporation of participatory methods, system learning, and collective resilience thinking for communities and decision makers. Some emergent DRI approaches take on an understanding of CAS in terms of uncertainty regarding index outputs (e.g., DBN; Kammouh et al. [133], and in terms of irreducibility and system framings (e.g., contextual exceptions, perceptual differences between stakeholders).

Recursive methods are also important because composite indices tend to be static when complex systems are in continuous evolution (i.e., urban systems are constantly changing). Such a process has two potential benefits in the effort toward robust metrics of disaster resilience. One, monitoring how variables change over time in respect to resilience outcomes can provide novel insights into key indicators for disaster resilience (i.e., longitudinal studies; Fekete, [29]. Different variables can emerge as critical between different disaster events due to slow variables that cause changes in urban systems over time, or changes in the nature of the event (e.g., hurricane intensity, frequency, or unprecedented events). Two, evaluating and re-evaluating the robustness and usefulness of indices post-application can address validation and contribute to index development. Applying DRI-driven resilience measures while investing in monitoring results can enable modification of methodological approaches as needed for different disasters or as resilience-related processes evolve, and contribute to urban resilience knowledge.

## 8.3. Broader implications and the future of resilience indices as a form of measurement

Resilience to disasters can range categorically from momentary failures to extended “Black Swan” events like COVID-19 (arguably a “black elephant”), and temporally from disruption to post-recovery periods [16,134]. While resilience index approaches can range from specific hazards like urban flooding, many of the dominant frameworks take an all-hazards approach (at least climatic hazards in general; [30]. Literature differentiates between specified resilience, which incorporates foreseeable risks in terms of a specific challenge or normative aim (“of what, to what”) that can be managed by best practices and infrastructure design, and general resilience, pertaining to the overall ability for systems to adapt and transform upon all types of shocks, including unprecedented ones [70,135]. Trade-offs exist between investments for specified versus general resilience [70,136].

As COVID-19 emerged during the writing of this paper, variables that emerged as critical hardly align with previously established core indicators for DRI, such as safe and equitable digital access, the ability to

isolate cases of infection, and multi-modal transportation [137–139]. Common indicators like emergency shelters and religious organizations promote specific resilience to disasters like hurricanes, but become problematic during disasters like pandemics. Established DRI methods may be more applicable when framed and developed in terms of a well-specified challenge. However, this should come with an understanding of potential trade-offs and limits in capturing elements of general resilience, such as the irreducible leadership and organizational elements that emerged as critical to COVID-19 [140,141]. Further research can clarify the validity and usefulness of proxies for systemic properties, such as the overall ability of an urban system to self-organize, toward indicating some type of general resilience.

From a broad complexity perspective, resilience indicators could aim to capture how resilience may emerge, rather than interpreting a place as having altogether “more resilience” than before, or relative to another place. Indices that can be decomposed interactively to pick apart indicators and indicator themes allow for this kind of observation, such as those that use GeoApp platforms where different levels of aggregations and layers of data can be dynamically viewed by planners and decisionmakers. Application-based indices become even more effective when applications support multiple layers of data that can qualify and add depth to indices like surveys and ethnographic descriptions (e.g. Ref. [142], or time series of index data. Creativity, reflexive use, and careful consideration of limitations and assumptions supports the effectiveness of DRI and enables them to evolve as complexity becomes a more prominent paradigm.

While there are arguments that the use of composite indicators and maps for resilience are insufficient, there is demand for such actionable and geographically oriented metrics [8]; see Ref. [88] for an argument in context of sustainability indicators). The usefulness of these kinds of metrics comes down to not only how they are developed, but how they are understood and applied. DRI provide a momentary snapshot of how a continuously evolving urban system may cope and recover from a disaster. Even a CAS-oriented framework for DRI aims to reduce a system to its essential moving parts. Some reduction is necessary to make sense out of the system and take resilience-enhancing actions. While composite index methods may eventually prove to be too simplistic for complex systems, such methods can be used algorithmically to understand urban processes, or coupled in holistic frameworks with other types of analysis and transdisciplinary knowledge for a fuller picture of urban resilience. When the uncertainty of CAS is properly addressed, there is still value in having a litmus metric for resilience capacities and capital to make the case for resilience investments, build community and infrastructure capacities, and satisfy the demand for expedient tools to cope and prepare for coming disasters.

## 9. Conclusions

This paper outlined trends and connections among urban disaster resilience and complexity literature, and a common core of DRI indicators was identified and analyzed against CAS tenets and SES resilience principles. We point out that resilience indicators could ultimately be categorized into two broad system dimensions: (i) essential forms of capital that act as stocks to support adaptation, and (ii) governance and community capacities that enable the flow of information and resources, and organization. Several review articles point to the necessity and difficulty of incorporating interactions between subcomponents and subsystems into index methods (i.e., system-of-systems).

An analysis of commonly adopted resilience concepts and indicators in terms of CAS tenets and resilience principles found that indicators only sometimes relate to systemic variables or proxy for the capacity of an urban system to reorganize after a disaster. DRI may be categorically misaligned with CAS by quantifying attributes of subsystems at one point in time and space, concatenating them to rank overall resilience (e.g., summative aggregation), and attributing meaningfulness to the subsequent index in terms of the process of urban response and adaptive

capacity amid disasters. This paper discussed alternative framings of concepts, indicators, and methods that can serve as better proxies to the emergence of resilience. DRI can be interpreted in terms of how indicators proxy the ways resilience may emerge, rather than a rank order between places and snapshots in time. Resilience as “anti-vulnerability” has been further distinguished from resilience as an adaptive process in a complex system. Further work toward resilience index research and development should include validation (either statistical or cross-validation via stakeholder engagement, mixed-methods, or short case studies), and coupling interdisciplinary methodologies. Methods like thick mapping and spatial ethnographies combine quantitative and qualitative data, and show potential avenues for furthering innovative approaches for resilience assessment. Along with network-based computational approaches, these research foci can enable researchers to understand nuances regarding indicators, observe exceptions and limitations to indices, and enable novel tools for practitioners to determine how to harness adaptive capacities in the face of future disasters.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This work was funded by the U.S. National Science >Foundation grants NSF CRISP-1832678, NSF SRN-1444755, and NSF GCR-1934933. The authors would like to thank Dr. Marty Anderies and the members of the NSF-CRISP Enhancing Resilience in Islanded Communities ([eric21.org](http://eric21.org)) team for many fruitful conversations that influenced this work, and two anonymous reviewers who provided thoughtful critique and feedback toward an improved version of this manuscript.

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