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Abstract

As natural disasters have increased in frequency and magnitude, there has been a growing need to understand the underlying factors that are likely to lead to faster recovery and more resilient communities. One way of addressing this need has been to develop sets of indicators or indicator indices that serve as proxy measurements for resilience, which is an emergent system property and cannot be directly measured.

Since the application of indicators can have profound effects on community well-being, it is important that indicator selection involves stakeholders and is based on the best available science. Previous reviews of resilience indicator frameworks have attempted to gauge the state of science used for indicator selection by looking for consensus of indicator choices across different frameworks.

Using a novel categorization methodology based in systems science, this study reviews a small set of resilience frameworks for indicator consensus. Compared to previous reviews, this methodology allows for a distinction between consensus of concepts and consensus of indicators to measure concepts. Our results show two new insights. First, common usage of an indicator does not mean that agreement exists on what the indicator is actually measuring. Second, even if there is agreement on what concepts are measured by an indicator, it is not guaranteed that this consensus is backed by high quality evidence. These results call into question the practice of reviewing many frameworks to identify common indicators during model development, and instead point to the need for more detailed assessment of background evidence and indicator validation.

Keywords

Indicators; interdependent infrastructure; resilience; systems.

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Acknowledgments

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Author Contributions

Gerst: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Dillard**: Conceptualization, Methodology, Project Administration, Supervision, Validation, Writing – review & editing. **Walpole**: Conceptualization, Formal analysis, Methodology, Writing – review & supervision. **Loerzel**: Conceptualization, Methodology, Validation, Writing – review & editing

1. Introduction

Over the past 20 years, the concept of resilience has emerged as a prominent concept in disaster research, emphasizing the dynamic and complex nature of pre- and post-disaster community states and responses. In tandem, resilience indicator frameworks have become increasingly common as both a methodology to study resilience and a decision support tool for disaster and adaptation planning. For decision support, they are seen as particularly attractive because indicators are tools that, if implemented correctly, confer salience, credibility, and legitimacy to co-produced efforts to track the effects of planning over time [1]. Furthermore, indicator research has illuminated what measurable variables and constructs might explain resilience, an unmeasurable latent variable, across communities.

As the body of resilience indicator research has grown, many reviews have been published in order to synthesize findings and highlight gaps in knowledge. Since the early work of Winderl [2] and the early NIST reports examining the space of community resilience measurement [3–5], at least 11 other large-scale reviews of resilience indicators have been published in the literature (Table 1). Most of these reviews look for commonalities among overlying conceptual models, dimensions (e.g., social; economic), indicators, and metrics, and find an array of definitions. In the end, these differences were found to be somewhat superficial, with many reviews reporting a large overlap in the underlying dimension concepts [6–9]. However, as Cutter [7] notes, this might be an artifact of most frameworks being derivative of a small set of early pioneering studies [10–13], as opposed to actual agreement on the conceptual foundations of resilience, which has both theoretical and empirical components [6].

Table 1. Large-scale reviews of resilience indicators

Author(s)	Year	Title
Winderl, T.	2014	Disaster resilience measurements: stocktaking of ongoing efforts in developing systems for measuring resilience
Ostadtaghizadeh, et al.	2015	Community disaster resilience: a systematic review on assessment models and tools
Lavelle et al.	2015	Critical assessment of existing methodologies for measuring or representing community resilience of social and physical systems
[a]Beccari, B.	2016	A Comparative Analysis of Disaster Risk, Vulnerability and Resilience Composite Indicators
[a]Shafari, A.	2016	A critical review of selected tools for assessing community resilience
[a]Cutter, S.	2016	The landscape of disaster resilience indicators in the USA
[a]Asadzadeh, et al.	2017	Operationalizing a concept: The systematic review of composite indicator building for measuring community resilience
[a]Bakkenson, et al.	2017	Validating resilience and vulnerability indices in the context of natural disasters

Author(s)	Year	Title
Koliou, et al.	2017	State of the research in community resilience: progress and challenges
Patel et al.	2017	What do we mean by 'community resilience'? A systematic literature review of how it is defined in the literature
Cai et al.	2018	A synthesis of disaster resilience measurement methods and indices
[a]Edgemon, L., et al.	2018/2019	Community Resilience Indicator Analysis: County-Level Analysis of Commonly Used Indicators from Peer-Reviewed Research
[a]Cutter, et al.	2019	Existing Longitudinal Data and Systems for Measuring the Human Dimensions of Resilience, Health, and Well-Being in the Gulf Coast
Cutter and Derakhshan	2019	Implementing disaster policy: exploring scale and measurement schemes for disaster resilience

[a]Reviews analyzed for reasonableness of use; see Table 6

Some reviews also assess the convergence of indicators used across studies. Often the most used are broadly applicable indicators, such as demographic and health indicators, that have been repurposed for measuring the social and economic domains of vulnerability [14, 15]. While some authors caution that indicator commonality among studies can be due to relative data availability and common use of seminal studies [16], others take the view that broader use is an indication of the measurement's credibility [17] or scientific consensus [18].

A few reviews move beyond finding commonalities and attempt to address appropriateness of indicator choices. Some use expert judgment to assess concepts such as scientific merit [5], representativeness [17], and information pedigree [16], while others focus on whether a framework has undergone a validation process [6, 14, 15, 17]. Reviews of validation processes highlight the challenges in externally validating resilience indicator frameworks. In particular, there is no agreement on what variables should be used as the outcome that the indicator framework predicts.

While these reviews have contributed to our knowledge of the commonalities across indicators as well as use of theoretical frameworks, there remains a gap in understanding whether or not convergence exists in how indicators link to the underlying aspects of a community and its resilience. This convergence is important for establishing that commonly used indicators are actually measuring similar concepts. For example, many frameworks may use housing tenure, but use it as an indicator of different concepts, such as attachment to place or economic vulnerability.

One option for answering this question is to adopt an existing theoretical underpinning and use it to interpret indicator choices from other frameworks. While at first appealing, this choice does not recognize that the theoretical conceptual models implicitly or explicitly propose a causal description of resilience, such as social capital affects a community's ability to recover and thus its resilience. If another framework does not use this causal description but uses a common indicator, then the comparison might not be meaningful.

Another solution, and the one adopted for this paper, is to create a non-causal conceptual model based on a system-of-systems approach that describes the system attributes of a community without hypothesizing causality. In the following sections, this method is used to consider seven operationalized frameworks; frameworks that are not operational were purposefully excluded to control for suggested indicators with no plan of measurement. This results in an assessment that allows for simultaneous exploration of the following questions, which previously have not been explored together: (i) what are the most common indicators, (ii) what are the most common components of the underlying conceptual model, and (iii) are common components measured in the same way across frameworks? While this analysis is a step forward, we, like others, note that commonality does not necessarily equal scientific consensus and cannot be used as a proxy for high quality of evidence for including an indicator. We close the paper with a discussion on next steps towards establishing science-based arguments for building indicator frameworks.

2. Methods

The framework analysis consists of two parts. The first was a process of defining a community resilience indicator framework and then using this definition to compile a list of frameworks to assess. The second part involved a qualitative analysis of each framework's content, producing a list of indicators and conceptual components.

2.1. Selection of frameworks

Framework selection proceeded over multiple stages, with early stages designed to efficiently identify and filter out frameworks and later stages designed to provide more detailed rankings. The first stage was to define the characteristics of a community resilience indicator framework so that existing frameworks and methodologies could be evaluated. From our knowledge of the field, ten characteristics were identified that should serve as foundational requirements for a community resilience measurement framework or methodology. The measurement framework or methodology should:

1. Employ systems level measurement
2. Measure at the community scale
3. Consider empirical relationships among systems (interdependencies)
4. Include temporal measurement, including the baseline or pre-event and post-event recovery stages
5. Be specific enough to be meaningful
6. Be practical for decision making
7. Link to resilience policies and actions
8. Be scientifically grounded
9. Be replicable
10. Be validated

Systems theory refers to the approach of understanding a system through an investigation of its components and relationships, as well as the properties and behavior of the entire system [19, 20]. While there is significant complexity in the interrelated systems of a community, a range of methods can be used to both reduce the complexity and shine a light on the important and useful indicators and measures that should be tracked over time. These methods include systematic review, exploratory and confirmatory factor analysis, and quasi-experimental designs [21]. Ideally, a community resilience assessment methodology would be applicable at a variety of spatial scales to be useful for a neighborhood, a small city, a large metropolis, or a county. Equally important is the capability for temporal measurement. In fact, it is essential due to the temporally dynamic nature of resilience. The state of resilience for any given community is related to both its pre-event attributes as well as post-event recovery stages [4, 22].

Further, the framework or methodology should be specific enough to be meaningful, linked to resilience planning, and practical to decision making. Community officials must both understand the outputs from a given assessment method and be able to use the methodology to support evaluation and development of meaningful policies to prepare for, withstand, and recover from a disruptive event [4, 21]. Finally, the methodology should be scientifically grounded, replicable, and validated. These last characteristics are necessary to instill confidence in the science behind any proposed community assessment methodology and to ensure that the indicators selected are tested for their ability to perform as valid predictors of resilience. The methodology should be formulated to predict measurable events, calibrated against past observations, and testable against future observations.

Using these 10 criteria of a community resilience indicator framework, 56 existing frameworks were identified to evaluate and systematically summarized in a dataset [3]. As previous reviews have noted, community resilience indicator frameworks are diverse, especially with respect to maturity level. The initial 56 frameworks considered varied from purely conceptual to fully implemented with quantifiable indicators. This is consequential for a review exercise because implementation level is highly likely to affect indicator choices, potentially introducing a bias into the analysis. Scientists partly choose indicators based on whether they are quantifiable, salient to the user, and scientifically defensible. Thus, a framework that is far from implementation might include more speculative indicators than an implemented framework that is constrained by data availability and user needs.

However, for this effort, the in-depth review was restricted to frameworks with a relatively high level of implementation. This was done to ensure that the frameworks in this analysis generally met the needs of practitioners and policy-makers looking to operationalize community resilience into their planning goals. The filtering process proceeded in two stages. The initial screening criteria were two yes/no questions: (i) could the framework be implemented? and (ii) could the indicators be quantifiable? Applying these criteria filtered out 24 frameworks that, in our judgment, could not be implemented or whose indicators are not quantifiable, for a total of 32 frameworks remaining.

The 32 remaining frameworks were then scored according to the criteria listed in Table 2. The criteria were used to maintain coordination with NIST's *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (Guide) [22, 23] and to align with the aforementioned requirements of a community resilience assessment methodology. For example, a framework had to be applicable at a community scale, broadly defined as "a place designated by geographical boundaries that functions under the jurisdiction of a governance structure, such as a town, city, or county" [22]. To be useful to community resilience planners, practitioners, or researchers, the framework should have been, or could be, implemented. The actual implementation of a framework speaks to both relative credibility of the method and its implied ease of use. Indicators must be quantifiable so that they may be tracked over time and space. This is necessary for pre-event and post-event (recovery) analysis of resilience and to identify leading and lagging indicators.

The ease of use requirement was applied to the frameworks in two contexts. First, the data needed for framework implementation must not be difficult to obtain, and secondly, the processes by which any data is to be collected must be able to be performed with minimal effort. The overarching goal for screening for ease of use is to keep the costs of implementation reasonable from a budgetary perspective yet still be able to characterize the community. Lastly, the framework had to produce results that were meaningful to community resilience. Specifically, the results could be related to a community's preparedness to prevent incidents, mitigate risk, protect assets, respond in a coordinated way, and/or recover community functions.

Table 2. Criteria for framework selection

Filter criteria	Scale
Is the framework generalizable to the community scale?	High/medium/low
Has the framework been implemented?	Yes/no
Could the framework be implemented?	High/medium/low
Are the framework indicators quantifiable?	High/medium/low
Is the framework easy to use?	High/medium/low
Is the framework meaningful to community resilience?	High/medium/low

After selecting the frameworks with the highest ratings (i.e., all "high's"), 8 remained. However, upon a review of the remaining frameworks another framework was removed from consideration. ARUP International Development's City Resilience Index was removed due to the very large number of indicators included in the framework (n=223) which could potentially skew the results of the analysis. In addition, it was believed that a large data collection would be difficult for a small community to accomplish. The final frameworks (Table 3) selected for coding are Baseline Resilience Indicators for Communities [7], Community Disaster Resilience Index [12], Mitigation Framework Leadership Group [24], Measuring Resilience and Vulnerability in Communities [25], Monitoring Well-being and Changing Environmental Conditions in Coastal Communities: Development of an Assessment Method [26], Resilience Capacity Index, and Social Vulnerability Index [27].

Table 3. Frameworks for in-depth review

Framework identifier	Framework full name	Framework citation
BRIC	Baseline Resilience Indicators for Communities	Cutter, S. L., Ash, K. D., & Emrich, C. T. (2014). The geographies of community disaster resilience. *Global Environmental Change*, 29, 65–77. https://doi.org/10.1016/j.gloenvcha.2014.08.005
CDRI	Community Disaster Resilience Index	Peacock, W. G. (2010). *Advancing resilience of coastal localities: Developing, implementing, and sustaining the use of coastal resilience indicators: A final report* (p. 148). Hazard Reduction and Recovery Center.
MitFLG	Mitigation Framework Leadership Group	USDHS. (2016). *Mitigation Framework Leadership Group (MitFLG) Draft Concept Paper: Draft Interagency Concept for Community Resilience Indicators and National-Level Measures.* U.S. Department of Homeland Security.

Framework identifier	Framework full name	Framework citation
MRV	Measuring Resilience and Vulnerability in communities	Miller, K. K., Johnson, A., & Dabson, B. (2016). *Measuring Resilience and Vulnerability in U.S. Counties* (Working Paper IPP/07). University of Missouri Harry S. Truman School of Public Affairs Institute for Public Policy.
NOAA	Monitoring Well-being and Changing Environmental Conditions in Coastal Communities: Development of an Assessment Method	Dillard, M. K., Goedeke, T. L., Lovelace, S., & Orthmeyer, A. (2013). *Monitoring Well-being and Changing Environmental Conditions in Coastal Communities: Development of an Assessment Method* (NOAA Technical Memorandum NOS NCCOS 174; p. 176). U.S. National Oceanic and Atmospheric Administration.
RCI	Resilience Capacity Index	Foster, Kathryn A. (n.d.) "Resilience Capacity Index." Building Resilient Regions.
SoVI	Social Vulnerability Index	Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social Vulnerability to Environmental Hazards. *Social Science Quarterly*, 84(2), 242–261. https://doi.org/10.1111/1540-6237.8402002

2.2. Qualitative Analysis

The frameworks were assessed using qualitative social science methods, primarily by a technique known as template or closed coding. This method seeks to categorize qualitative concepts in the data by first developing a set of labels or ‘codes’ from the existing literature. These codes are then applied to the data, reviewed for their validity and usefulness, and then modified as needed [28].

For this study, initial application, revision, and finalization of codes followed an iterative process to account for the inherent subjectivity of qualitative analysis. One framework at a time, at least two coders independently applied codes to the framework document and assigned confidence levels to assigned codes. If a coder had low confidence or there was disagreement in the code assigned, the team proceeded to resolve discrepancies through expert judgment and discussion. This process led to refinement of the codes and their definitions. After all seven frameworks were coded, one team member checked the overall dataset for consistency in the application of codes across frameworks. Any discrepancies were flagged for further discussion by the team.

The initial set of codes was created by assuming that ‘community resilience’ is an emergent property of the interaction of many interdependent system types [11, 21]. Thus, each indicator can be described by the system it refers to (system type), the system behavior it describes (system indicator type), and the name of the indicator itself (indicator). The reviewed frameworks sometimes use slightly different measures for the same indicator (e.g., % households with a vehicle and % households without a vehicle) or label measures as indicators, which makes comparison across frameworks difficult. As a result, a common list of indicator names was created and applied to each indicator. Similar to Beccari [14], a hierarchical set of indicator names was created to organize common concepts at varying levels of specificity. For example, an indicator of housing tenure might have housing at the highest level, then housing tenure, and finally owner-occupied at the lowest level.

For system type (Table 4), a distinction is made between systems that support a community, such as food, health, and governance, and the community itself, which we define as a group of people within a defined geographic area that have some degree of shared values, beliefs, and norms. The system types span the range from natural systems (i.e., environmental) to social (i.e., community) to socio-technical. For socio-technical systems, the system boundary is drawn to extend from the effect the system has on a community and its members, such as education attainment or health outcomes, to the system's physical infrastructure and institutions. The final 16 system types are shown in Table 4.

Developing the coding scheme for system indicator types drew from two overlapping fields of indicator literatures: program evaluation and vulnerability/resilience (Table 5). The program evaluation literature, which is popular in evaluating the effectiveness of education and health programs, distinguishes among process, output, and structural indicator types [29–31]. Process indicator types describe inputs to a system, while output indicator types describe outcomes or other system behaviors that represent system goals or objectives. For example, a community input indicator is the number of civic organizations, and a corresponding community output indicator is the average time residents have lived in a community, which is an indicator of a community's sense of place or belonging. *Structural indicator types* are synonymous with what are called non-functional requirements in systems engineering, which describe how a system performs while achieving its goals [32]. Examples of structural indicator types are system availability, affordability, accessibility, adequacy, and susceptibility. Common program evaluation indicator types were combined with indicator types from the vulnerability/resilience literature [33]. Some indicator types from this literature, such as susceptibility, have the same definition as in program evaluation. However, others such as hazard, exposure, response, and impact, are unique to vulnerability/resilience assessment.

The final 11 system indicator types are listed in Table 5. Outcomes refer to objectives or goals of a system. While these might not be explicitly set by a planner or system designer, outcomes generally align with a system's purpose. For example, community systems exist to, among other things, provide a sense of place, belonging, and mutual support; housing exists to provide adequate shelter. Hazards and impacts are linked in that hazards are events with the potential to disrupt systems, such as a flood event, and impacts describe the actual effect of disruption, such as buildings damaged due to a flood event. Thus, not every hazard leads to a disruptive impact.

Inputs are a mix of program evaluation and vulnerability/resilience indicator types. Expenditures indicator types track spending or budget items, while responses are activities that occur to adapt to future disruptions or to cope from a past or current disruption. For input indicators that do not meet either of these definitions, a general code of process is used.

Structural system indicator types encompass the behaviors of each system. The concepts of availability, accessibility, affordability, and adequacy are taken from health and education system program evaluation. These attributes are often seen as key factors to improving system outcomes. In the context of the results, accessibility, affordability, and adequacy have relatively narrow definitions. In contrast, availability encompasses both the traditional sense of system capacity and the concept of response capacity found in the vulnerability/resilience literature.

They are included under the same concept because, in practice, the same indicators often apply to both. The system attributes of exposure and susceptibility also take their concepts from commonly accepted definitions in the vulnerability/resilience literature. Exposure describes a situation where a system location could lead to impacts from a hazard, and susceptibility measures whether a system is inherently likely to have impacts from a hazard event.

Table 4. System types used in coding resilience frameworks

System type	Definition
Environmental	areas minimally managed that are not intended to primarily provide services and benefits to communities
Physical environment	areas created and/or managed with the intention that they provide a service/function to meet the needs of communities
Community	processes or spaces which provide a sense of place, belonging, or mutual support
Governance	formal institutions that enact, enforce, and manage public goods and services. These services can support the provisioning of other systems such as education and public safety and security
Economic	businesses, financial systems, and aspects of a community's livelihood which support a community (e.g. goods and services produced, employment and compensation, and financing), or serve as inputs into other systems
Public safety and security	social services (e.g., family services), emergency management, and law enforcement systems which facilitate the safety and security of communities in multiple ways (e.g. crime rates, emergency disruptions, and child welfare)
Education	all levels of education, from programs that lead to a degree to ones that provide training over a short timespan, which influence community characteristics (e.g. literacy rate)
Health	facilities and resources which improve the physical and mental health of community members, including the prevalence of disease, life expectancy (or morbidity/mortality), birth rates, and health status
Food	the agricultural, distribution, and sales components of growing and bringing food to communities, resulting in a properly nourished population and reducing instances of food insecurity
Housing	structures which provide adequate shelter to a population, including physical dwellings, or lack thereof. Also includes temporary and emergency housing, hotels/motels, and shelters
Buildings	structures used for non-residential services and purposes (e.g. businesses, storage facilities)
General infrastructure	used for indicators not specific to the four more infrastructure systems defined (communication, energy, transportation, and water)
Communication	infrastructure that provides the means with which communities exchange information, including newspapers and electronic forms of information technology, resulting in a connected and informed community
Energy	infrastructure that provides energy to communities, including the generation, transmission, distribution, and use of energy
Transportation	infrastructure that provides a means to move to and from destinations within communities, including the modes of walking and cycling, public transportation, as well as the use of private automobiles; also includes transportation in support of economic activity (e.g. freight, rail)
Water	infrastructure that provides and manages potable water, controls stormwater, and manages wastewater

Table 5. System indicator types used in coding resilience frameworks

System indicator type	Definition
Outcomes	high-level goals of a system; for example, for the community system, if an indicator measures providing a sense of place, belonging, or mutual support, then it is an outcome
Hazards	natural events that have the potential to lead to system disruption
Impacts	the effect of a disruption on outcomes
Inputs	activities within a system that affect outputs or structural factors
Expenditures	are a specific type of process dealing with spending or budgets
Responses	activities that occur to adapt to future disruptions or to cope from a past or current disruption
Process	used as the code for all process factors that are not expenditures or responses
Structural	properties of the system itself; measure the ability of the system to deliver outcomes
Availability	the capacity of a system regardless of whether that capacity is accessible, affordable, or adequate
Accessibility	physical or information barriers
Affordability	cost barriers
Adequacy	quality or acceptability of a system's outputs
Exposure	the degree to which something is in a location that could lead to impacts from a hazard (e.g. living in a flood plain)
Susceptibility	the degree to which something is inherently likely to suffer negative consequences from a hazard (e.g. having generators, etc. located in basements); A person or system can be exposed but not susceptible (e.g. you live in a floodplain but your house is very flood-proofed) or susceptible but not exposed (e.g. your home is not flood-proofed but located up on a hill)

3. Results

3.1. Framework comprehensiveness

One metric that can be useful for framework comparison is comprehensiveness, which is measured by the number of system types and system indicator types that are included. In terms of comprehensiveness, some frameworks are less comprehensive by design. For example, SoVI and RCI do not include environmental or physical environment system types and offer little coverage of infrastructure and the built environment (Fig. 1). As a result, they only include 50% and 44% of potential system types, respectively (Fig. 2). In contrast, BRIC, CDRI, MitFLG, NOAA, and MRV cover the full range of environmental hazards, social factors of vulnerability, and infrastructure indicators, covering anywhere from 75 % to 94 % of potential system types.

Further distinction can be made based on the comprehensiveness of system indicator types. All frameworks include at least one indicator type for community, governance, economic, health, and housing systems. However, the number of system indicator types included for each framework varies considerably: CDRI and MRV include one attribute for housing, while NOAA includes five. Similarly, SoVI and MitFLG include two indicator types for the community system, while NOAA includes five. Part of these differences come from differing framework design and goals. For example, NOAA has a particular focus on capturing the many dimensions of community well-being. In contrast, MitFLG has a stronger focus on infrastructure, with a more comprehensive system and indicator type coverage in this area.

While there appears to be some relationship between the number of frameworks including a system type and the percent of frameworks including two or more system indicator types, there is some notable variability (Fig. 3). For example, environmental, public safety and security, food, communication, and transportation are all included in five frameworks. However, only one of the five frameworks (CDRI) have more than one system indicator type for communication, while three frameworks (BRIC, SoVI, and NOAA) have more than one system indicator type for food, and four frameworks have more than one system indicator type for environmental (CDRI, MitFLG, NOAA, and MRV), public safety and security (BRIC, MitFLG, NOAA, and MRV), and transportation (BRIC, CDRI, MitFLG, and MRV).

Broader framework-level patterns in the comparison of system and indicator types can be seen by comparing the percent of system types included in a framework, the percent of included system types that have two or more indicator types, and the overall number of indicators. As shown in Fig. 2, one grouping emerges, where between 75 % and 94 % of systems are included in the framework and between 58 % and 64 % of included systems have two or more indicator types. Within this group, there is considerable variation of the number indicators in the framework, ranging from a low of 32 in MitFLG to a high of 90 in CDRI.

The NOAA framework has a similar percentage of included system types (81 %), but has considerably more system types with two or more indicator types (77 %). Thus, its 55 indicators are spread relatively efficiently across many system and indicator types. In contrast, SoVI, with 41 indicators, has similar indicator type comprehensiveness as the NOAA framework (75 %), but includes only 50 % of system types. RCI is an outlier in the set; it has relatively low system and indicator type comprehensiveness and includes the smallest number of indicators (17). Despite these differences, some areas of convergence are evident. Of the system types that are included in all frameworks (community, governance, economic, health, and housing), at least half of the frameworks cover two or more system indicator types (Fig. 3). In the case of the community system type, all frameworks include two or more indicator types. This might indicate some consensus on community being a multidimensional concept that cannot be adequately captured with one indicator, which is explored in more detail in the next section.

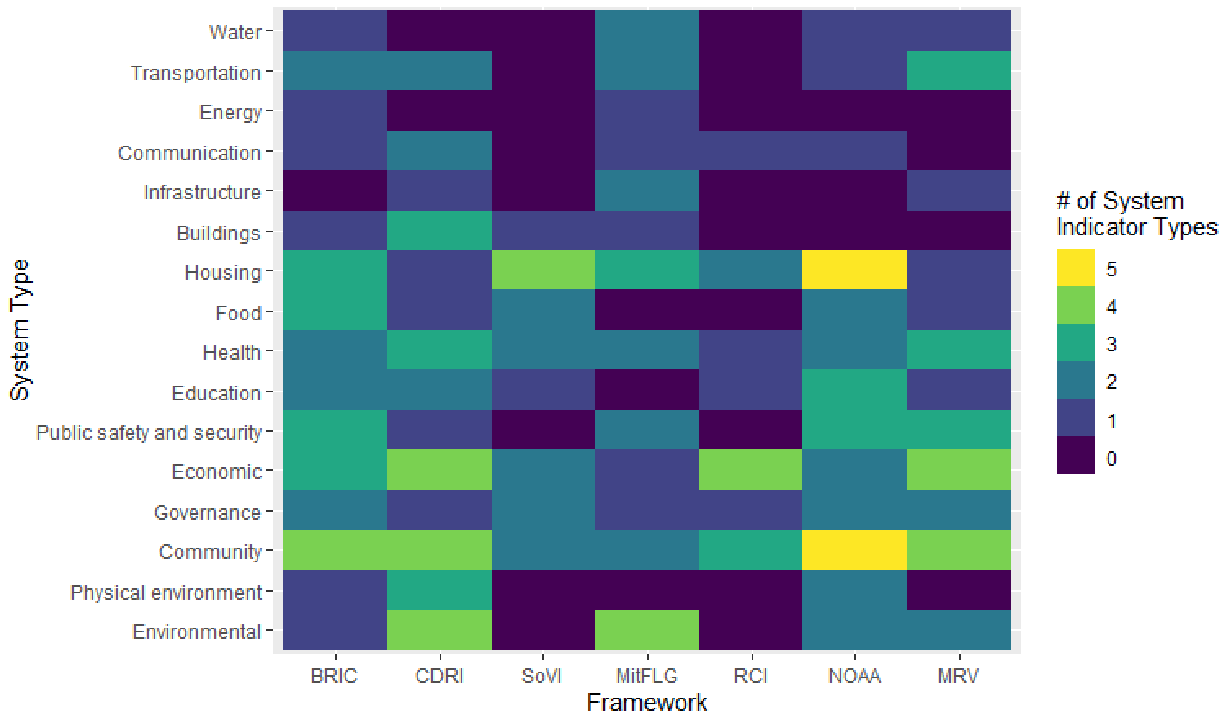

Fig. 1. System types included in frameworks.

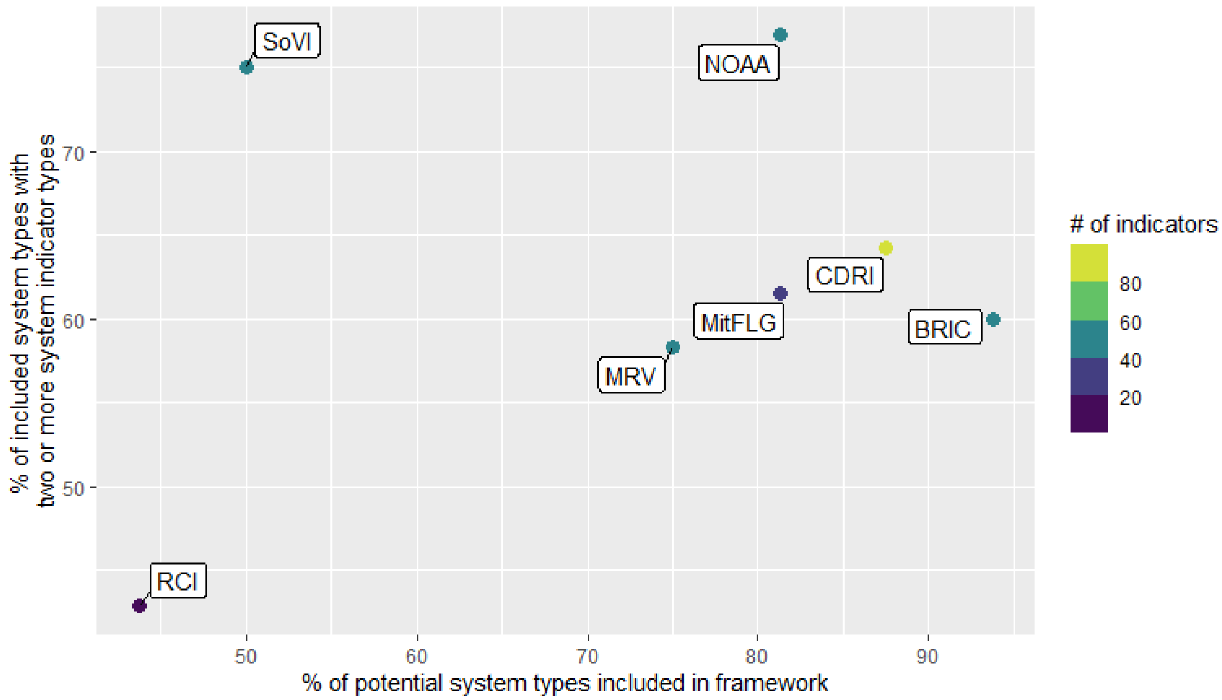

Fig. 2. Percentage of potential system types included in frameworks versus percentage of system types with two or more system indicator types included in the frameworks.

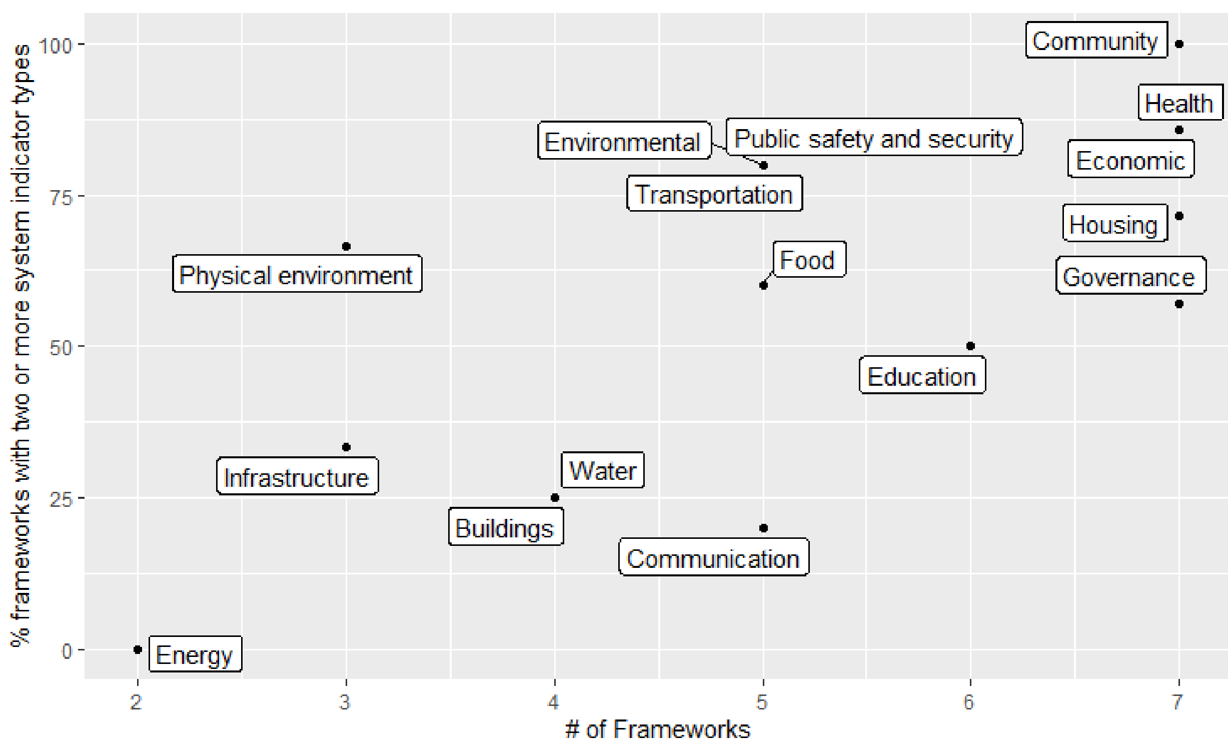

Fig. 3. Number of frameworks versus percentage of frameworks with two or more system indicator types included.

3.2. Overall system and indicator types coverage

Across system types, the most common indicator types are outcomes, availability, and susceptibility (Fig. 4). In general, outcomes are system goals that stakeholders ultimately care about; it is expected they would be prominent in any indicator framework. Availability and susceptibility are multi-dimensional concepts that are prominent in the conceptual framing of resilience; thus their frequent use is not surprising. Availability encompasses structural attributes such as overall system capacity as well as response capacity for coping and adaptation. Susceptibility addresses structural attributes related to system reliability under normal circumstances as well as propensity of sustaining impact during a hazard event.

Some system types, such as housing, contain a particularly rich set of attributes. This is because housing enters the casual chain of resilience at more than one point. Housing can have structural properties that are relatively easy to measure, such as age or type of materials, that affect exposure and susceptibility. In addition, availability of accessible, affordable, and adequate housing figures into housing outcomes that influence community well-being as well as availability of response capacity during a hazard event. Other socio-technical systems, such as communication, food, and health, have similar properties, but the reviewed frameworks did not measure these systems as comprehensively as housing.

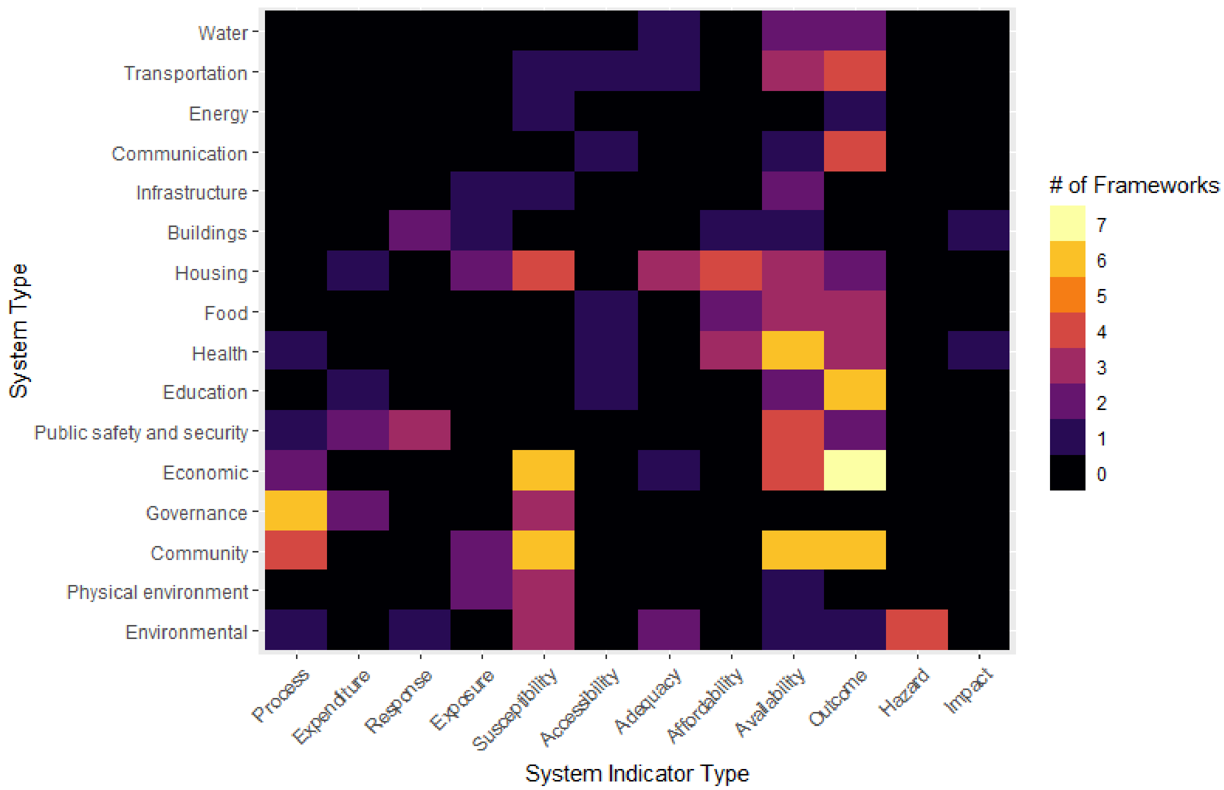

Fig. 4. Number of frameworks for each system type and system indicator type combination.

An important feature of our coding scheme is that it provides a consistent way to categorize indicators across frameworks that have different conceptual underpinnings. This becomes especially useful when frameworks use multiple indicators per system type for distinguishing the kind of multidimensional measurement the framework is proposing. For example, for economic systems, at least one framework measures a process, susceptibility, adequacy, availability, or outcome indicator type. Of these, four or more frameworks measured susceptibility, availability, and outcome indicator types (Fig. 4).

Within these four system indicator types, multiple indicators may be measured, in part because the indicator types themselves are multi-dimensional, or there may not be agreement on what indicator to use. For economic outcome indicator types, neither multi-dimensionality nor disagreement provide complete explanations. Seven different indicators were found for outcomes, with medium to strong agreement on five of them: income, income inequality, poverty, laborforce participation rate, and unemployment rate (Fig. 5). Two frameworks, SoVI and MRV, include them all. For the other five frameworks, laborforce participation rate and unemployment rate appear to be options for measuring the same macroeconomic outcome, as none of the five use both. Income inequality and poverty, which could be considered another pair of substitutable indicators, do not appear to be used as such. In contrast, susceptibility of the economic system appears to have more convergence, with indicator choices concentrated on regional economic vulnerability or sector size indicators.

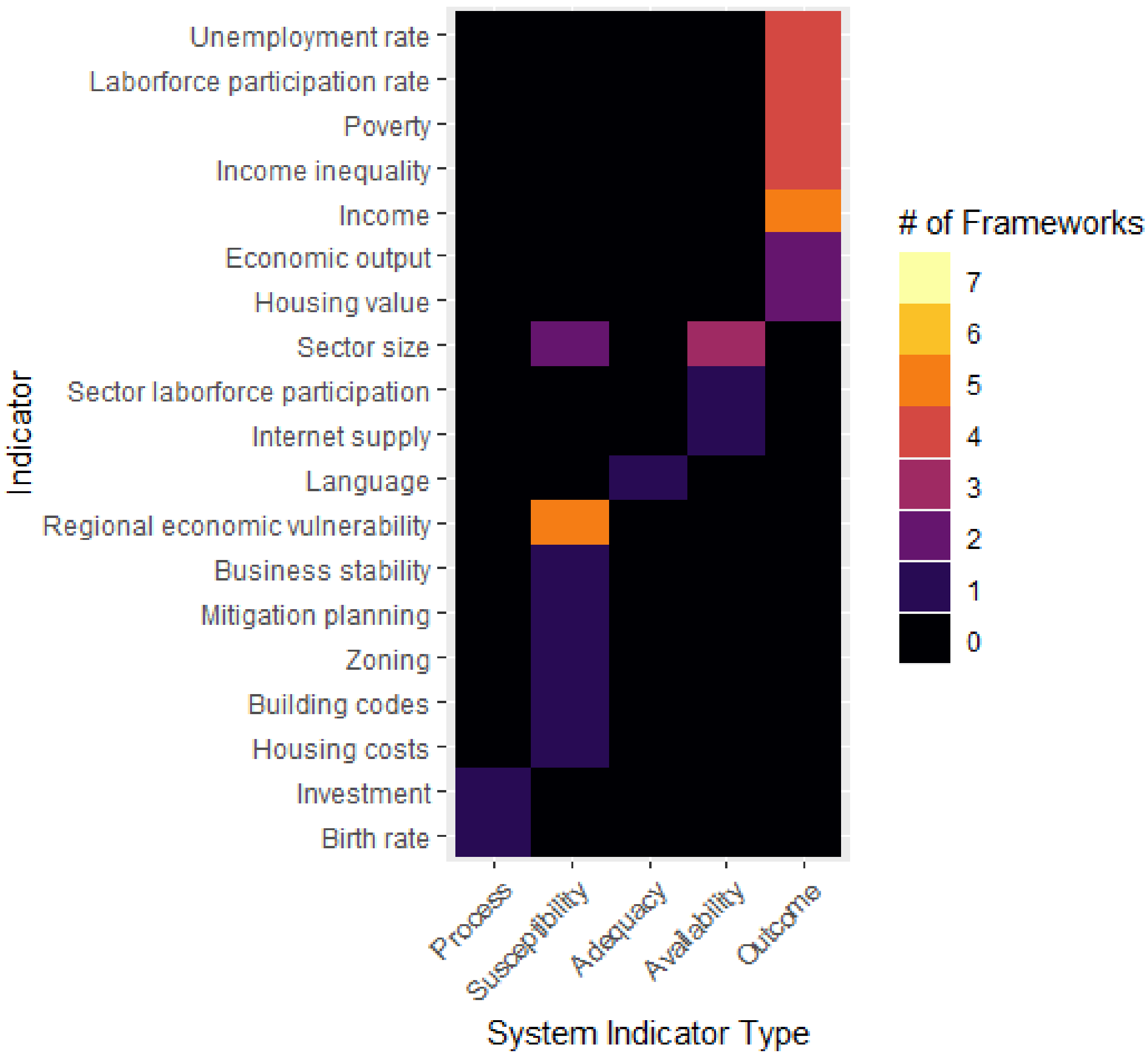

Fig. 5. Number of frameworks for each system indicator type and indicator combination for the economic system type.

The community system is another example (Fig. 6). While there is convergence on the number of civic organizations being an indicator for community availability, there is less agreement for susceptibility and outcomes. Four frameworks use age (i.e., % young and/or % elderly population) as an indicator for susceptibility, three frameworks use the percent of population with a disability, and two frameworks use the percentage of the population speaking a non-English language. Two frameworks, BRIC and MRV, include all three of the susceptibility indicators, while SoVI, RCI, and NOAA only include one. With the exception of MitFLG, all frameworks provide some measurement of connection to place, which is an important outcome of communities. The most frequent concept utilized is internal migration, a measure of what percent of the population has been in the same place over a specified unit of time.

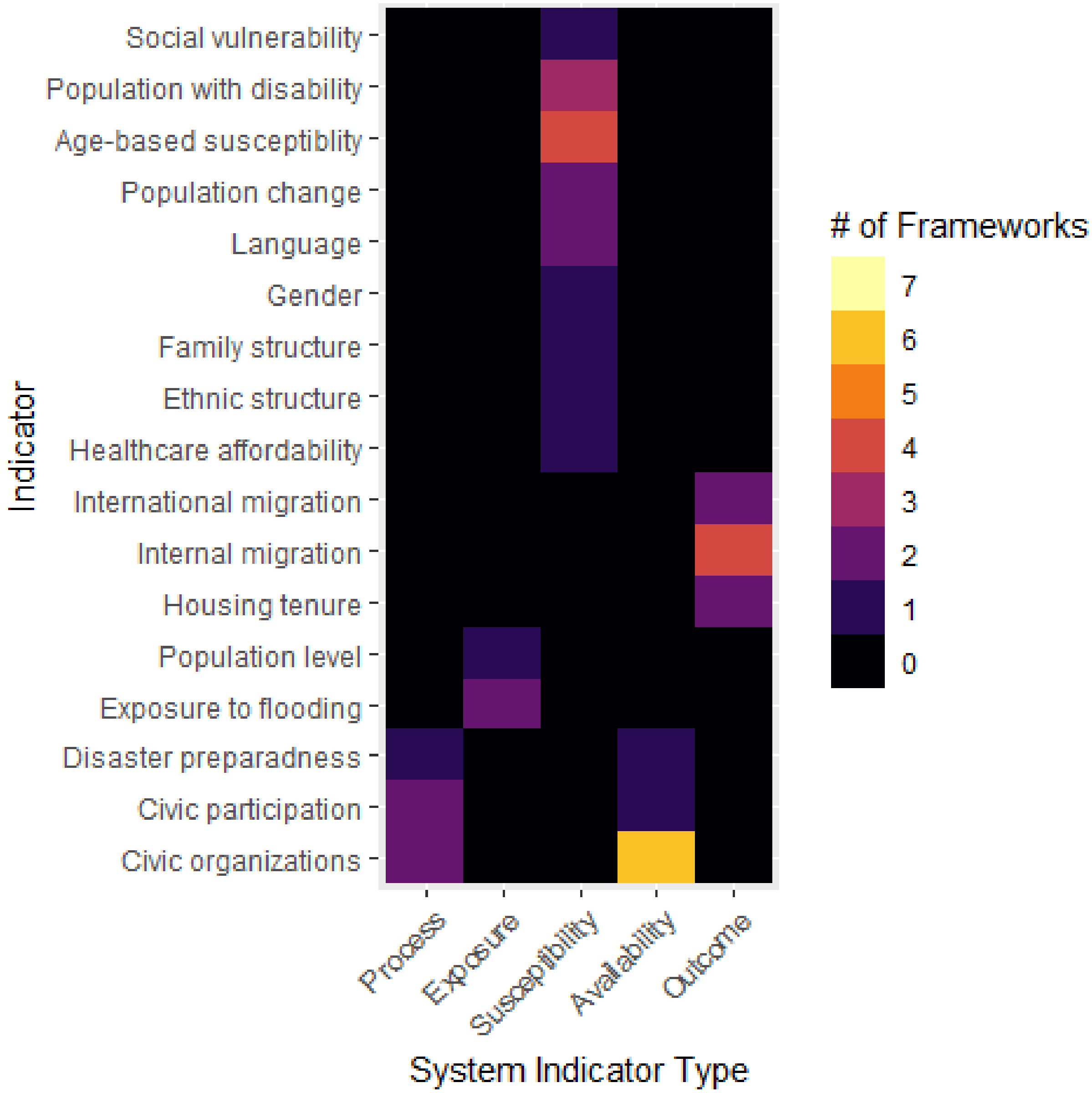

Fig. 6. Number of frameworks for each system indicator type and indicator combination for the community system type.

Similar patterns are observed for other system types. Housing, for example, has four frameworks measuring susceptibility and affordability. The two most predominant indicators for susceptibility are housing age and housing construction type. BRIC and MRV include both indicators, while SoVI and NOAA include one or the other. For affordability, three frameworks use housing costs, while one uses housing value. Availability of public safety and security, which is measured by four frameworks, is another example, as measurement for this system indicator type is spread across five different indicators.

More concentrated areas of agreement between system indicator type and indicator were seen for other areas. Three of these pertain to outcomes: four or more frameworks matched (i) education attainment and education outcome, (ii) household telephone service access and telecommunication outcome, and (iii) household vehicle access and transportation outcome. Two availability areas are related to health: number of physicians and number hospitals/beds. The only process indicator that emerged as any sort of consensus was voting participation, which is used for the governance system.

3.3. Most common indicators

An indicator is defined as being common if it is used in four or more of the seven frameworks reviewed for this study (Table 6). Under this definition, the analysis results in 18 common indicators. None of the indicators were used in all seven frameworks, but three indicators (voting, educational attainment, health system laborforce) were used in six frameworks and three indicators (civic organizations, regional economic vulnerability, and housing tenure) were used in five frameworks. Despite the relevant strictness of the inclusion filter, most of the indicators found to be common for the seven frameworks were also found to be prevalent across seven other indicator reviews that conducted similar analyses (see Table 1). Notable exceptions are voting, regional economic vulnerability, housing cost, telephone service, and flood exposure, which other reviews did not find to be as prevalent.

Of the 18 indicators, 14 are consistently used with one system and indicator type pair. For example, voting is consistently used as a community process indicator type. Of the four indicators that are not used consistently, two highlight the dual role cost can have in an indicator framework. Housing costs are used in three frameworks as an indicator of housing affordability and in one framework as an indicator of economic susceptibility. Similarly, health insurance is used in three frameworks as an indicator of health affordability and in one framework as an indicator of community susceptibility. Differences occur because of how frameworks contextualize the role of these two indicators. In particular, MRV more explicitly positions these indicators as community-related. Another indicator, housing tenure, highlights how the same indicator can be used to measure two different outcomes: sense of place, which is a community system outcome, and overall owner-occupied rate of the housing stock, which is a housing system outcome.

Table 6. Common indicators and measures with assessment of frequency and reasonableness.

Indicators	Measures	Frequency of use (Number of frameworks, n=7)	Common in other reviews (Number of reviews, n=7)
Voting	Voter participation rate in Presidential election, proportion registered voters	6	2
Educational attainment	Proportion of population with secondary education attainment, Proportion of population with tertiary education attainment, Tertiary/secondary ratio	6	6
Health system laborforce	Number of physicians	6	5
Civic organizations	Number of non-profit organizations, Number of civic organizations	5	7

Indicators	Measures	Frequency of use (Number of frameworks, n=7)	Common in other reviews (Number of reviews, n=7)
Regional economic vulnerability	Sector diversity index, concentration of vulnerable sectors	5	3
Housing tenure	Proportion of all housing units owner-occupied, Proportion of all housing units renter-occupied	5	6
Healthcare infrastructure	Number of hospitals, Number of hospital beds	4	5
Housing cost	Median monthly housing cost, Median monthly rent	4	1
Age-based susceptibility	Proportion of population over 65 years of age, Proportion of population under 18 years of age (or under 5 years of age)	4	5
Vehicle access	Proportion of households with a vehicle, Proportion of households without a vehicle	4	5
Unemployment	Unemployment rate	4	6
Laborforce participation	Laborforce participation rate	4	4
Poverty	Proportion of population living at or below poverty, level, Proportion of children living at or below poverty level	4	4
Income	Income per capita, Median household income	4	6
Inequality	Gini index, Gender income inequality index, Proportion of households with incomes above $200K	4	6
Telephone service	Proportion of households with telephone service	4	2
Flood exposure	Population in flood zone, population close to dam/levee	4	1
Health insurance	Population with health insurance, population without health insurance	4	4

4. Discussion

This effort sought to identify patterns and commonalities among the indicators used in community resilience assessment frameworks. Beginning with a review of 56 community resilience frameworks, they were filtered using specific criteria (Table 2), which resulted in the seven community resilience frameworks used in this analysis. Using a novel systems measurement framework, the indicators from these frameworks were categorized into 16 system types and 11 system indicator types. Using a harmonized list of indicator names, indicators were then analyzed for frequency of use, with 18 indicators being used in four or more frameworks.

While system type comprehensiveness varies widely across frameworks, all include at least one indicator type for the system types of community, governance, economic, health, and housing systems. For the community system type, all frameworks include two or more indicator types. Across all system types, the most frequent indicator types are outcomes, availability, and susceptibility. Among these commonly found systems and indicator types, some agreement is found for a few measurements: (i) education attainment as an education outcome, (ii) household telephone service access as a telecommunication outcome, and (iii) household vehicle access as a transportation outcome, and (iv) number of physicians as health system availability. While relatively few process indicators were found, voting participation was found to be a commonly used governance process indicator.

Having identified some areas of common usage brings this study back to the original motivating question of whether consensus exists for certain indicators, and if so, what does it mean? After careful review, we share the skepticism expressed in Cutter [7] that emerging consensus on how resilience should be measured might be more a function of biased reliance on a small number of foundational studies and repeated use of convenient data sources, and less a reliable signal that there is good evidence for a clear underlying conceptual model with an unambiguous linkage to indicator measurement.

For example, for the frequently used indicator of voting, the evidence cited by frameworks for using voting as an indicator appears to largely center around the work of Putnam [34] on social capital and democracy. Both CDRI and NOAA cite this work directly, while BRIC is based on Norris et al. [11] and Sherrieb et al. [35], which cite a small set of other social capital theorists. MRV cites BRIC and SoVI is based on earlier work by Cutter [36]. As acknowledged in CDRI, social capital is difficult to measure, and it often covers both individual (e.g., strength of networks) and public (e.g., voting and civic participation) social capital. As a result, many frameworks include multiple measures using easily obtained data, including voting participation and other frequently used measures such as the number of civic organizations.

This points to a fundamental challenge for using social capital and many other difficult-to-define concepts in resilience indicator frameworks. If used broadly or imprecisely, then a framework risks including social capital as both a cause and effect [37]. In practice, this often manifests as using an indicator as both a contributor to, and a measure of, social capital. This dilutes the utility of an indicator system, which by design is supposed to simplify the causal chain of a complex system [33]. Even if used appropriately, reviews of the effects of individual or public social capital on disaster resilience highlight the observation that results are mixed and context-dependent. Furthermore, there is a lack of longitudinal or comparative empirical research, which is necessary to distinguish causal mechanisms pre- and post-disaster [38]. According to common quality of evidence guides, this combination of low generalizability and lack of appropriate empirical studies points to low quality of evidence.

In contrast to the voting indicator, the number of physicians indicator does not appear to have a convergent conceptual or empirical source. However, it is similar in that most frameworks either cite each other or another framework or review article. For example, MitFLG cites BRIC, which in turn cites the foundational work of Norris et al. [11] as well as the literature review of Chandra et al. [39]. Both of these latter sources emphasize that although the number of physicians indicator is conceptually plausible, there is not overwhelming empirical support. The sources of evidence listed for CDRI, Smith et al. [40] and Keeley [41], both discuss the importance of health in maintaining human capital, but there is no explicit link to the number of physicians as an indicator. Only the NOAA framework provides a set of empirical studies that directly address this indicator. Bodenheimer and Pham [42], cited by the NOAA framework, documents the decline in and maldistribution of primary care physicians in the US, noting problems of lack of access leading to long waits or unreasonable travel times to see a physician, while Joynt et al. [43] compares outcomes from rural critical access hospitals to non-critical access hospitals in the U.S., showing some explanatory effect for lack of staffing resources.

Other studies from the literature, but not cited by the frameworks, appear to reinforce the importance of the number of physicians to health outcomes. For example, Chang et al. [44] found that among U.S. Medicare beneficiaries in 2007, areas with more primary care physicians had lower mortality rates and ambulatory sensitive condition hospitalizations. Basu et al. [45] found a similar pattern across a longer timeframe and broader age demographic, with physician numbers being associated with greater life expectancy. Further analysis is likely needed to establish that any specific indicator can be credibly used to provide guidance for resilience-related planning and decision-making. Depending on the data availability, this analysis could take the form of external validation against outcomes, such as fatalities or property damage from a disaster.

One of the reviews assessed, Bakkensen et al. [6], uses a regression model to test the explanatory power of different composite indices. However, limiting the analysis to composite indices, as opposed to the set of indicators, does not give much information about the validity of which indicators are included. Testing sets of indicators will likely require a more sophisticated approach, because doing so combines measurement and causal models. Indicator validation exercises in other fields such as education have utilized structural equation models because of their ability to test the relationship among many latent and observed variables.

If data availability is poor, then the promising avenue of structural equation modeling might not be possible. Alternatively, providing better justification from the literature for indicator choices could improve indicator credibility. The most likely option to improve indicator justification is through systematic review. However, systematic reviews can be very time consuming and unwieldy to document in indicator frameworks that contain almost 100 indicators. Thus, there might be value in the resilience indicator community collaborating to set standards for summarizing evidence and to produce a series of systematic reviews on commonly used indicators.

Ultimately, establishing the scientific basis for resilience indicator frameworks is more than an academic exercise, as these frameworks have the potential to be used for planning and funding decisions and program assessments, which have real impacts on communities. Thus, it is critical to establish that indicators are backed by adequate evidence and are validated. Failing to do so can erode trust of stakeholders or can lead to decisions that are not helpful for already vulnerable communities.

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