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Key Points:
- Conceptual model of community resilience to climate events
- Climate event resilience must be holistic and include vulnerability and recoverability
- This conceptual model is being populated for application for the U.S. at the county level

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Conceptualizing holistic community resilience to climate events: Foundation for a climate resilience screening index

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ABSTRACT The concept of resilience has been evolving over the past decade as a way to address the current and future challenges nations, states, and cities face from a changing climate. Understanding how the environment (natural and built), climate event risk, societal interactions, and governance reflect community resilience for adaptive management is critical for envisioning urban and natural environments that can persist through extreme weather events and longer-term shifts in climate. To be successful, this interaction of these five domains must result in maintaining quality of life and ensuring equal access to the benefits or the protection from harm for all segments of the population. An exhaustive literature review of climate resilience approaches was conducted examining the two primary elements of resilience—vulnerability and recoverability. The results of this review were examined to determine if any existing frameworks addressed the above five major areas in an integrated manner. While some aspects of a resilience model were available for existing sources, no comprehensive approach was available. A new conceptual model for resilience to climate events is proposed that incorporates some available structures and addresses these five domains at a national, regional, state, and county spatial scale for a variety of climate-induced events ranging from superstorms to droughts and their concomitant events such as wildfires, floods, and pest invasions. This conceptual model will be developed in a manner that will permit comparisons among governance units (e.g., counties) and permit an examination of best reliance practices.

1. Introduction

A community's ability to endure and recover from abrupt system shocks is an important factor for sustainability. Adverse events can take many forms, but there is no place on Earth immune to natural disasters. Acute climate events often impose significant and long-lasting effects that can impact human and natural systems alike. The concept of resilience has been evolving over the past decade as a way to address the current and future challenges nations, states, and cities face from a changing climate. The intersection of society and the natural and built environments in context of governance and risk underlies the concept of resilience. Understanding how these aspects reflect community resilience for adaptive management is critical for envisioning urban and natural environments that can persist through extreme weather events and longer-term shifts in climate, while maintaining quality of life and ensuring equal access to the benefits or the protection from harm for all segments of the population.

Resilience is "the ability of a system to recover from perturbation; the ability to restore or repair or bounce back after a change due to an outside force" [*Meadows*, 2008]. Similarly, the National Research Council defines resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" [*NRC, National Research Council*, 2012]. Both definitions assume that the threat of exposure to some shock exists (vulnerability) and that the ability to recover (recoverability) from a shock is intrinsic or planned. In this sense, resilience sits at the crossroads of two elements; vulnerability and recoverability. Many articles addressing resilience focus on one or the other of these elements [e.g., *Cutter et al.*, 2003; *Flanagan et al.*, 2011]. Much of the literature reviewed defined vulnerability as a combination of exposure, sensitivity, and adaptive capacity with adaptive capacity representing recoverability. By representing recoverability collectively as adaptive capacity, the ability to differentiate community governance and provisioning of services from personal recoverability is lost. Further, existing literature rarely describe the specific vulnerability exposures that necessitate recovery capacity.

However, to truly examine resilience not only must both vulnerability and recoverability be addressed but information to help communities identify their potential issues of resilience in each element must also be assessed.

Any discussion of community resilience should address both natural ecosystems and human communities in tandem since both are intrinsically connected to people and their well-being [*Summers et al.*, 2012]. Much of the existing resilience literature describes natural and human systems—separately. In terms of adverse climate events, natural and human systems are often described, either directly or inadvertently, in opposing roles [*Handmer et al.*, 2012]. However, few would argue that the services that ecosystems provide are invaluable for reducing vulnerability or improving recoverability [*Summers et al.*, 2012, 2016]. From that perspective, natural systems are important factors to consider when addressing community resilience.

Both natural and human systems can absorb, recover from, and adapt to adverse events [*Gunderson*, 2010; *Berkes and Ross*, 2013]. Natural ecosystems rely on innate internal structures and functions for recovery. Clearly, natural ecosystems "plan and prepare" for adverse events through their internal structures and functions (e.g., diversity and redundancy) [*Holling*, 1986; *National Fish*, *Wildlife and Plants Climate Adaptation Partnership*, 2012; *Melillo et al.*, 2014]. Human systems may use planning and preparedness to mitigate vulnerabilities and strengthen recovery weaknesses [*Tobin*, 1999; *Magis*, 2010]. Given these similar resiliency characteristics, it makes sense that a truly holistic measure of community resilience accounts for the status of integrated socio-ecological systems, well-being of people, and nature.

As part of a broader sustainability paradigm, a fuller accounting is necessary to characterize the influence of management decisions on aspects of resilience, relative to economic, social, ecological, and political factors. A comprehensive, integrated concept of progress is needed to better understand resilience to climate change and its relationships with external drivers (economic, ecologic, and social) and mitigating factors. Success, however, depends on breaking down the barriers to integration and collaboration across sectors enabling community planners, emergency managers, health and ecological professionals, and other key governmental and nongovernmental stakeholders to come together around a shared goal of resilience. The end result will be a community that is healthier, more livable, and better prepared for future adversities, today, and for future generations.

The U.S. EPA is developing a scalable climate resilience screening index (CRSI) for the U.S. A composite index of resilience is a much needed measure for evaluating comparative adaptability and tracking progress toward climate resilience across the nation. The purpose of CRSI is to characterize resilience for the nation and help EPA and communities prioritize activities to increase positive resilience outcomes in the face of climate change impacts, more specifically, acute climatic events. The approach for developing the index will incorporate changes in community governance, socio-economic drivers, mitigating forces, and natural ecosystem structure and function that contribute to changes in resilience to climate events. CRSI may serve as a valuable measure for understanding the impacts of resilience-focused decisions on overall community well-being.

This paper suggests an approach framework and core set of resilience indicators linked to economic, social, and environmental resilience in context of risk and governance. This holistic examination of resilience will permit communities to review their current circumstances (at the nearest spatial scale), identify weaknesses in their climate-related resilience, and leverage resilience characteristic information about other similar communities to enhance local resilience to climate change events. The application of this approach will be addressed in a companion manuscript produced at a later time.

2. Review of Existing Resilience Indicator Literature

Discussions with community and climate resilience experts (both within EPA program and regional staff as well as academia) helped identify general themes related to climate-resilience topics common across most communities. In addition, an extensive literature review was conducted to help define community characteristics that influence or are influenced by status of resilience. These characteristics were grouped into categories or *domains* to provide tangible focal points for assessing the status of community resilience in terms of adverse climate-related impacts. To conduct the initial review, Publish or Perish software (28 July 2015) provided the pool of available literature made public from 2000 to 2015, using the keywords "resilience index," "ecosystems," "social," "economic," "human well-being," and "climate change." This effort produced

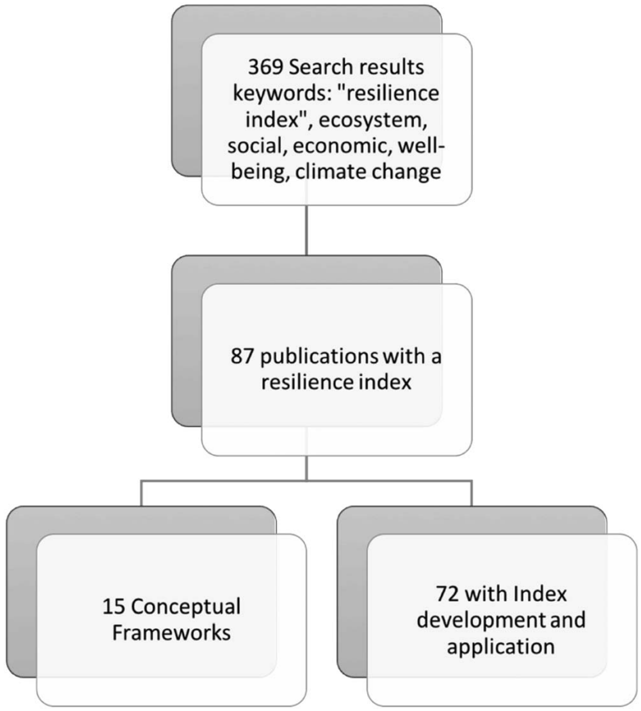

Figure 1. Summary of initial literature review.

369 results (Figure 1). The initial collection of published material was reviewed to differentiate “developed” indices from “conceptual” frameworks. A subset of 72 individual publications served as the basis for the formal review (Figure 1).

The final subset of existing measures were evaluated as presented to determine if a singular index or descriptive framework could meet research needs without modification. Accounting for multiple applications of a single index or framework, the review effort identified 27 publications with spatially scalable index models. From these available “resilience indices,” 587 domains/indicators were identified along with 1180 associated metrics (Table 1).

Review results showed that vulnerability dominates climate resilience measures. This is not surprising since vulnerability is the first step toward defining climate resilience (i.e., risk or exposure) [*Balica*, 2012; *Batica*, 2015]. However, vulnerability alone is not sufficient to characterize climate resilience. Areas that are vulnerable to climate events (towns, cities, counties, and states) must also have the ability to recover in order to demonstrate resiliency to these events. In recent literature, climate resilience indices have examined and included recoverability but usually to the exclusion of vulnerability or referred to it independently as previous work [e.g., *Cutter et al.*, 2014]. Climate resilience is the coupling of climate event vulnerability with the capacity to recover from an event should it happen.

The majority of indices measure the vulnerability of differing areas of the globe to climate change or climate events [e.g., *Alessa et al.*, 2008; *Joerin and Shaw*, 2011; *ARUP*, 2014] and largely ignore assessing and measuring how those areas would recover from such exposures although one paper [*ARUP*, 2014] touts recovery as the primary goal of climate resilience. The value of recovery holds the promise of a community’s ability to “weather the storm” and return to some level of stability. Identifying the linkages between climate vulnerability and event recoverability is key to understanding the intrinsic nature of community climate resilience. Without this understanding, the ability to prepare for and fully recover from adverse climate events is largely unattainable. None of the reviewed indices accomplished this coupling adequately, although one set of approaches (Social Vulnerability Index and Baseline Resilience Indicators for Communities (BRIC)) has addressed the multiple needs in different manuscripts [*Cutter*, 1996; *Cutter et al.*, 2003, 2014].

Our desire to have communities that are minimally impacted by climate events is nearly impossible without a strong recoverability plan and its execution following an event. These plans and their execution maintain a community at a significant distance from ecological, economic, and social tipping points (e.g., stability, sustainability, joblessness, social inequity, ecosystem and condition). Little attention has been given to the interconnectedness of the aspects of well-being [*Summers et al.*, 2014] as they relate to a community’s climate resilience. A community may be naturally vulnerable to climate events or vulnerable through anthropogenic activities, but its resilience to these vulnerabilities is driven by the combination of environmental, social, economic, and governance drivers.

We could not identify a singular approach among existing composite measures of climate resilience to use as an overall framework representing vulnerability and recoverability. Collectively, however, the reviewed literature provided building blocks (e.g., suites of indicators, indicator groupings, and domains) for developing a

Table 1. Existing Measures of Climate Resilience Included in This Review, the Number of Domains/Indicators, and Metrics Used in Each Measure

Index	Domains or Indicators	Metrics	Index	Domains or Indicators	Metrics
Agriculture Resilience Index [*Ciani*, 2012]	11	27	Composite Measure of Ecological Integrity [*Vickerman and Kagan*, 2014]	22	22
Artic Water Resource Vulnerability Index [*Alessa et al.*, 2008]	9	22	Displacement Risk Index [*Esnard et al.*, 2011]	15	51
Baseline Resilience Indicators for Communities [*Cutter et al.*, 2014]	49	49	EJ Screen Index [*US EPA*, 2015]	12	12
City Resilience Index [*ARUP*, 2014]	12	12	Environmental Performance Index [*Hsu et al.*, 2016]	20	20
City Resilience Index to Sea Level Rise [*Abdrabo and Hassaan*, 2014]	6	13	Environmental Sustainability Index [*Esty et al.*, 2005]	21	76
Climate Disaster Resilience Index [*Joerin and Shaw*, 2011] [*Peacock et al.*, 2010]	2538	12082	Environmental Vulnerability Index [*Pratt et al.*, 2004]	50	50
Community Resilience Index [*Kafle*, 2012; *Renschler et al.*, 2010]	6	29	Flood Resilience Index [*Batica*, 2015]	43	91
Community Resilience Index for the Gulf of Mexico [*Baker*, 2009]	30	30	Flood Vulnerability Index [*Balica*, 2012]	19	19
Community Risk Index [*Daniell et al.*, 2010]	27	46	Household Resilience Index [*Cassidy and Barnes*, 2012]	16	16
Composite Measure of Coastal Community Resilience [*Li*, 2011]	6	27	Metrics for Community Resilience to Disaster [*Burton*, 2015]	22	75
Composite Measure of Community Resilience [*Meher et al.*, 2011]	52	130	Resilience Factor Index [*Ainuddin and Routray*, 2012]	16	17
Composite Measure of Regional Resilience [*Martini*, 2014]	7	27	Resilience Inference Measurement Model [*Li*, 2013; *Lam et al.*, 2016]	10	33
Composite Measure of Resilience to Disasters [*Kusumastuti et al.*, 2014]	22	63	Sustainable Society Index [*van de Kerk and Manuel*, 2014]	21	21

new *climate resilience screening index* (CRSI) to address the needs of EPA. Figure 2 shows the proposed CRSI structure represented by five thematic subindices, 11 domains of assessment focal areas, and 28 identified indicators to quantify domains. A "heat map" table (Table 2) depicts the metric distribution across the indicators identified in the CRSI structure from each of the selected published indices.

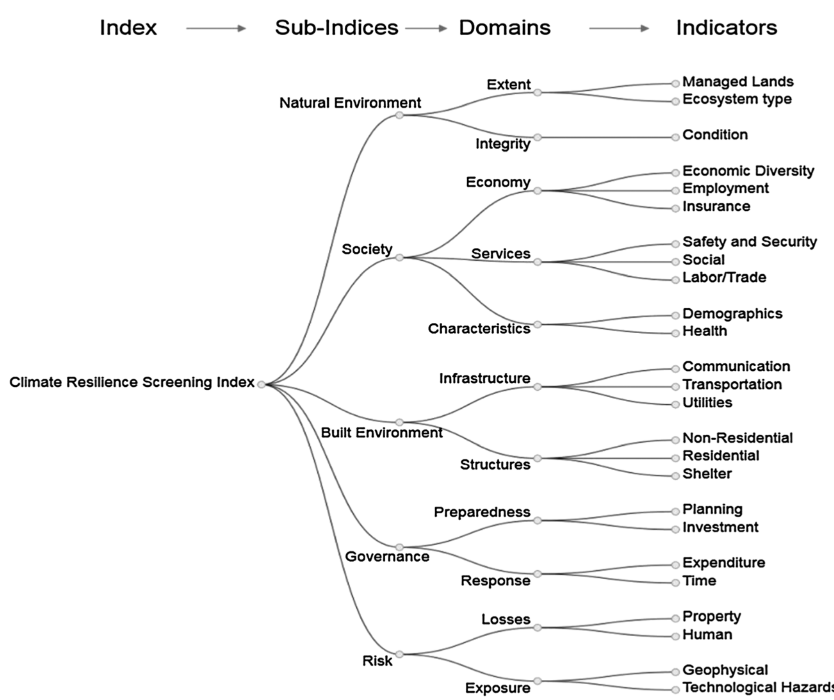

Figure 2. The proposed structure of the climate resilience screening index (CRSI) with identified subindices, domains, and indicators.

Table 2. Number of Existing Resilience Measures Distributed Across Proposed CRSI Structure[a]

CRSI Structure [Sub-index | Domain | Indicator]			Selected Index/Framework																										
			ARI	AWRVI	BRIC	CRI	CRISLR	CDRI1	CDRI2	CResI	CRIG	CRiskI	MCCR	MCR	MRR	M-RD	M-EI	DRI	EJSI	EPI	ESI	EVI	FRI	FVI	HRI	M-CRD	RFI	RIMM	SSI
Natural Environment	Extent	Managed Lands																											
		Ecosystem Typ.																											
	Integrity	Condition																											
Society	Economy	Economic Div.																											
		Employment																											
		Insurance																											
	Services	Safety & Security																											
		Social																											
		Labor/Trade																											
	Characteristics	Demographics																											
		Health																											
Built Environment	Infrastructure	Communication																											
		Transportation																											
		Utilities																											
	Structure	Non-Residential																											
		Residential																											
		Shelter																											
Governance	Preparedness	Planning																											
		Investment																											
	Response	Expenditure																											
		Time																											
Risk	Losses	Property																											
		Human																											
	Exposure	Geophysical																											
		Tech. Hazards																											

Existing Measures: No shading = 0 1 3 5 10 20 +

[a]ARI, Agricultural Resilience Index; AWRVI, Arctic Water Resource Vulnerability Index; BRIC, Baseline Resilience Indicators for Communities; CRI, City Resilience Index; CRISLR, City Resilience Index to Sea Level Rise; CDRI1, Climate Disaster Resilience Index 2011; CDRI2, Community Disaster Resilience Index 2010; CResI, Community Resilience Index; CRIG, Community Resilience Index for the Gulf of Mexico; CRiskI, Community Risk Index; MCCR, Composite measure of coastal community resilience; MCR, Composite measure of community resilience; MRR, Composite measure of regional resilience; M-RD, Composite measure of resilience to disasters; M-EI, Composite measures of ecological integrity; DRI ,Displacement Risk Index; EJSI, EJ SCREEN Index; EPI, Environmental Performance Index; ESI, Environmental Sustainability Index; EVI, Environmental Vulnerability Index; FRI, Flood Resilience Index; FVI, Flood Vulnerability Index; HRI, Household Resilience Index; M-CRD, Metrics for community resilience to disasters; RFI, Resilience Factor Index; RIMM, Resilience Inference Measurement model; SSI-Sustainable Society Index.

Of the 27 indices reviewed, 10 included information relevant to describing all five subindices of the proposed CRSI structure. However, none of the indices reviewed captured measures addressing all the domains in the CRSI framework. The natural environment, governance, and risk domains were most frequently excluded from existing measures. Five indices (BRIC, Climate Disaster Resilience Index 2011 (CDRI1), Community Disaster Resilience Index 2010 (CDRI2), Composite measure of resilience to disasters (M-RD), and Metrics for community resilience to disasters (M-CRD)) were missing information for six or fewer CRSI identified indicators. The Climate Disaster Resilience Index 2011 (CDRI1) contributed the most to the proposed CRSI structure, addressing all subindices, all domains with the exception of loss in the risk subindex, and 25 of the 28 indicators identified.

3. Constituents of CRSI: Subindices and Domains of Community Resilience to Climate Change

Measures culled from the selected literature base were classified into one of the 28 suggested CRSI indicators that are distributed across proposed domains and related subindices (see Table 2). In this section, each CRSI subindex is described including a brief discussion regarding candidate domains and indicators. A summary follows highlighting areas where CRSI seeks to strengthen community climate resilience assessments.

3.1. Natural Environment

The natural environment is a subindex that encompasses all living and nonliving things, occurring naturally in the United States. The concept of natural environment can be distinguished by two primary components: (1) complete ecological units that function as natural systems without extensive human inventions (often called ecosystems) and (2) universal natural resources and physical phenomena that lack clear-cut boundaries (e.g., air, water. climate, radiation, and magnetism) not originating from anthropogenic activities.

In this subindex the natural environment is represented by two domains—the extent and integrity of natural ecosystems and managed lands. The extent domain includes the spatial extent or acreage of each ecosystem type that occurs naturally (without any significant human intervention, e.g., wetlands, boreal forests, deserts, and lakes) and managed lands that occur with some human intervention (e.g., agriculture, silviculture, and aquaculture). The integrity domain is related to metrics that describe the condition of those ecosystem types and managed lands.

3.2. Society

The concept of society includes all the cultural, nonstructural elements of the built environment. These are the constructs that represent the economic, demographic, and social interactions common to all urban and rural populations. Society is a group of people involved in persistent social interaction or a large grouping of people sharing the same geographical or social territory. These groups typically are subject to some political authority and often similar dominant cultural expectations. More broadly, a society may be characterized as an economic, social, industrial, or cultural infrastructure made up of, yet distinct from, a collection of individuals. Thus, society can include the objective and subjective relationships people can have with the material world and other people.

Proposed society domains in CRSI include services, economy, and characteristics. The services domain includes aspects of safety and security, social services, and labor/trade. Safety and security services encompass the availability of emergency first responders, medical personnel, civil order, and legal services. Metrics included in safety and security would demonstrate a community's ability to respond and the timing of that response to the results of a climate event (e.g., flood, hurricane, tornado, and wildfire). Labor and trade services represent the availability of skilled labor and tradecraft that can be utilized in the aftermath of a climate event (e.g., carpenters, bricklayers, engineers, roofers, construction workers, and civil servants). Social services include the availability of services unrelated to infrastructure, labor/trade, emergency services, and civil control yet important for a community's response to a climate event. These services would relate to laws, childcare, education, healthcare, and faith-based organizations.

The economy domain includes insurance, social economic diversity, and employment. These indicators represent a society's ability to monetarily respond and recover from a climate event. Insurance or insurability relates to numbers of people and structures/property that are insured which can initiate recovery with an infusion of cash to start rebuilding [*Cutter et al.*, 2009]. Economic diversity relates to the array of business sectors a community might have. Lack of business sector diversity can suggest a more difficult path for economic recovery [*Adger et al.*, 2005a; *Reusch et al.*, 2005; *Adger*, 2010]. Employment and employment conditions can be important for a community's recoverability. This indicator would include metrics like unemployment rates, underemployment rates, and the formation of human capital [*Marston*, 1985; *Cohen*, 2011; *Peiró et al.*, 2015].

The characteristic domain of CRSI describes the demographics, health characteristics, and social cohesion of a region, state, county, or community. These attributes of a community can clearly influence or modify the recoverability of that community to a climate event. Demographics of a community reflect attributes of the community's general population, namely, age structure, ethnicity, and socio-economic levels. All of these factors can influence the ability of a community to recover from a disaster [*Lugo*, 2000; *Vasquez-Leon et al.*, 2003; *Heltberg et al.*, 2009; *Ibarrarán et al.*, 2009; *Steinbruner et al.*, 2013]. The general health characteristics of a population are also an element of the characteristics domain. These characteristics emphasize conditions associated with greater vulnerability to climate events such as respiratory or cardiac condition changes during periods of intense heat; hospitalization conditions requiring electronic equipment during times of loss of power during floods, hurricanes, or tornadoes; or injuries or premature death related to extreme weather events [*Greenough et al.*, 2001; *McMichael et al.*, 2003, 2006; *Melillo et al.*, 2014]. Social cohesion can be an important element of recoverability after a climate disaster. Social cohesion represents community and family-centric networks and value structures with an emphasis on the characteristics that increase the likelihood of vulnerability (e.g., sense of place) and/or recoverability (e.g., family and social networks) [*Schwartz and Randall*, 2003; *Adger et al.*, 2005b; *Baussan*, 2015].

3.3. Built Environment

The concept of a built environment is relatively recent, and it was initially coined by social scientists [*Rapoport*, 1976]. The "built environment" describes the man-made surroundings that provide the setting for human activity, ranging in scale from buildings, parks, green, and parks to neighborhoods and cities that can often include their supporting infrastructure, such as water supply, energy networks, and transportation corridors. The built environment is a material, spatial, and cultural product of human labor that combines physical elements and energy in forms for living, working, and playing [*Roof and Oleru*, 2008]. In recent years, public health research has expanded the definition of built environment to include healthy food access, community gardens, "walkability," and "bikeability" [*Lee et al.*, 2012]. The urban fabric is a complex socio-technical system that encompasses different scales—buildings, building stocks, neighborhoods, cities, and regions—each with different time constants, actors, and institutional regimes. The term built environment has also been adapted to address the relation between the built and the "unbuilt" parts of the environment. This corresponds to the definition of a socio-ecological system where the built environment can be considered as an artifact in an overlapping zone between culture and nature, with causation occurring in both directions. The sustainability debate, the growing awareness of risks to the built environment due to climate change, and climate events have all helped to focus attention on the fragilities and the need to create resilience in the built environment [*Hassler and Kohler*, 2014].

In CRSI, we have included two primary domains in the built environment subindex to represent the importance of built environment in resilience to climate events. These are structures and infrastructure. The structure domain addresses residential and nonresidential buildings as well as the subject groups' (states, counties, cities, and communities) capacity for shelters (i.e., this can be any building that can be designated as a shelter in the event of an emergency). The infrastructure domain addresses communication, transportation, and utilities, which are part of the fabric of man-made environments. These elements of society can be essential in assessing resilience as they provide the ability for widespread physical communication through television, wireless communications, radio, and landlines; arterial corridors for evacuation and transport of recovery materials; and basic needs such as water, water treatment, energy provision, and general connectivity.

3.4. Governance

"Governance" describes the collaboration of government agencies and nongovernmental (private) actors (e.g., nongovernmental organizations, companies, and citizens) toward joint objectives within a system of rules and regulations (hierarchies, markets, networks, and communities) [*Benz*, 2001; *Leisbet and Marks*, 2003;

Bache and Flinders, 2004a, 2004b]. Consequently, governance includes both formal and informal coordination processes among, across, and beyond different sectors of public administration. It has been increasingly recognized that resilience problems related to climate events can only be sufficiently handled in an integrative and adaptive way to include diverse policy fields from all scales [*Benz*, 2001] and actors from different fields [*Huitema et al.*, 2009; *Pahl-Wostl et al.*, 2012; *ARUP*, 2015]. However, the administrative systems of many U.S. federal, state, city, and community agencies are predominantly sectorally organized making coordination a major challenge in the wake of a severe climate event, such as flood protection and sea level rise [*Adger*, 2001; *Adger et al.*, 2005b; *Pahl-Wostl*, 2007; *Urwin and Jordan*, 2008; *Knieling and Filho*, 2012], storm readiness [*Wachinger et al.*, 2013; *Adger et al.*, 2011], water/river basin management [*Cosens and Williams*, 2012], and fire protection readiness [*Abrams et al.*, 2015]. In light of these challenges, governance requirements for improving collaboration between sector-administrations, governmental, and nongovernmental actors and new forms of governance must be introduced (e.g., integrated coastal zone management for storm events and oil spills) to bolster state, county, and community abilities to recover from climate-related severe events [*Crowder et al.*, 2006; *Ramseur*, 2010; *Colten et al.*, 2012].

In CRSI, we have included two primary domains in the governance subindex to represent the importance of governance in resilience to climate events. These are preparedness and investment/response. The preparedness domain addresses subject groups' (states, counties, cities, and communities) abilities to plan for exposure to climate events, to develop programs that will respond after these events, and to train and test their personnel regarding the intricacies of these plans and programmed responses. The investment/response domain addresses these entities' histories and abilities to invest and expend resources for climate event preparedness and to develop the response mechanisms required to provide postevent support as described in the preparedness domain.

3.5. Risk

The risk subindex of CRSI represents the characteristics of a place that contribute to a level of exposure or vulnerability resulting from specific hazards (climatic events, e.g., sea level rise, hurricane, tornado, wildfire, and drought). Risk, as a construct, is typically represented as the likelihood that severe alterations in the functioning of a place will occur as the result of the interaction of hazard, exposure, and vulnerabilities. Within the CRSI framework, hazards and exposures are dealt with wholly within the risk subindex, while vulnerabilities are dealt with across multiple subindices. While certain vulnerabilities are represented within the risk subindex (e.g., losses), other components are spread among the other subindices (e.g., economic, social, and built). These characteristics are those more typically the focus of intervention in efforts to increase resilience.

Most geologic and atmospheric hazards generally cannot be controlled, and only the likelihood of an event occurring in a specific timeframe can be calculated. In the climate resilience arena, this is the likelihood that a storm might occur, that sea level will rise by a certain amount, a wildfire would occur, or extremes in rainfall totals would occur in certain areas. The location of human and natural populations along with the built environment with regard to the likelihood of a threat results in this potential for exposure. The vulnerability of these systems is the potential for harm as a result of this exposure. Some assets (e.g., a community or built environment) can be constructed in the floodplain of river, enhancing its vulnerability to flooding, or a natural ecosystem (e.g., wetland) can be located near an area chosen for oil drilling, enhancing its vulnerability to exposure to oil. Similarly, managed ecosystems (e.g., managed forests and agriculture) can be constructed in drought prone areas, enhancing vulnerability of the managed products without water supplementation. In short, vulnerability can be "treated" by identifying weaknesses and taking proactive measures to correct identified vulnerabilities, for example, building dykes or levees (although these mitigation structures can actually attract or maintain unsafe development in flood prone areas), locating assets at some distance from threatened areas, or irrigation. Thus, risk, the intersection of threat, asset, and vulnerability can be mitigated or managed to either lower vulnerability or the overall impact of a threat on an asset. In essence, this is the approach that CRSI takes—identifying the exposures (likelihood of climate events, locations of assets in the form of natural environments, and built environment), assessing vulnerability by the inclusion of socioeconomic factors, and examining the mitigation or recovery of vulnerability through preparedness, governance, and execution.

In the CRSI model, risk is characterized by two domains—exposure and losses. The exposure domain addresses a subject group's (region, state, county, city, and community) likelihood of hazard occurrence

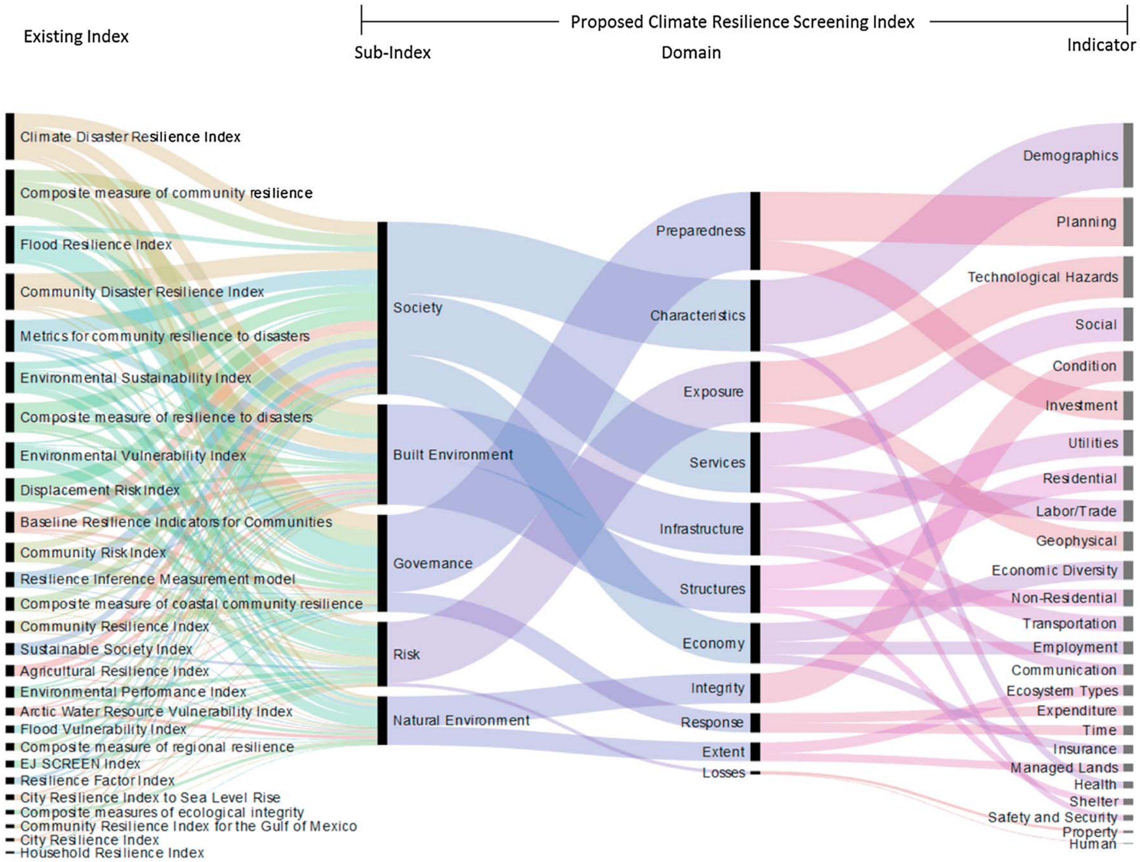

Figure 3. Contribution of existing measures to proposed subindex, domain, and indicator structure of CRSI. Columns are arranged (top) greatest to (bottom) least number of available measures. Flow paths indicate the relationship and relative contribution weightings of related indicators/measures for each existing index.

across a full spectrum of geologic and atmospheric events as well as additional technological hazards that may coincide or be exacerbated by the events. Proposed exposure domain in the CRSI conceptual index includes geophysical and technological hazard indicators. The geophysical indicator represents the likelihood of occurrence of a geologic or atmospheric hazard based on location of populations (human and nonhuman) and built environment. This indicator would be represented by multiple metrics that characterize both historic and forecasted likelihoods of hazard occurrence. Examples of these metrics would be the percentage of developed land impacted by fire, the percentage of developed land impacted by hurricane force winds, percentage of developed land impacted by modeled sea level rise of one foot, percentage of natural lands (nondeveloped) impacted by inland flood events, or forecasted rainfall in inches. The technological hazard indicator represents an area's likely exposure of built technologies (e.g., nuclear power plants, oil pipelines, and chemical manufacturing) to climate events as well as the potential for the coincidence of these events and technological hazards to impact nearby human populations. Examples of metrics for this indicator could include number of leaking underground storage tanks per unit of area or population, percentage of agricultural/ managed lands exposed to aquatic emissions, or proportion of population residing within unsafe limits of managed superfund or other identified toxic waste site.

The loss domain addresses an aspect of a place's vulnerability represented through historical loss of life and property (including crops) associated with specific hazards. The property loss indicators describe estimated and actual costs associated with property and crop losses as a direct result of a hazard. Many of the potential metrics for this indicator would come from the Spatial Hazard Events and Losses Database (SHELDUS; http://hvri.geog.sc.edu/SHELDUS/). Similarly, the human loss indicator represents the loss of human life directly resulting from a hazard with metrics largely coming from the SHELDUS database.

3.6. Integrating the Domains and Utility to Users

To assist communities and stakeholders who work closely with communities, it is important to offer a way to not only identify the status of resilience in the face of current adverse climate events but to help them identify areas of strengths and weaknesses. Similar to existing indices, CRSI provides a snapshot of resilience conditions while the components present a closer look at the drivers of measured condition. Where CRSI differs is in it representation of the total environment in which people live and the dynamism of factors that are outside of their control (e.g., risk) yet must be considered to sustain resilience over time (e.g., governance). Figure 3 depicts the relative contribution of the 27 existing indices toward a holistic view of community resilience.

The majority of measures identified from the reviewed indices reflect demographic characteristics of the society subindex. Although governance and risk subindices were frequently excluded from the existing measures of resilience, those indices addressing these areas were focused primarily on preparedness reflected in planning and investment measures for governance and exposure to technological hazards for risk. Human and property loss as measures of risk were the least frequently included measures. The built environment subindex of CRSI was well represented across many of the indices. The fewest number of measures across indices were assigned to the natural environment subindex; however, condition indicators were well represented. The extent of ecosystems and managed lands was represented in the reviewed indices less frequently. Addressing a community's resilience to climate events must be in reality a holistic assessment. Resilience assessment can be approached in a piece-meal fashion, but this approach generally results in numerous unintended consequences of the actions taken. Using a holistic conceptual approach coupled with utilization of appropriate existing data and collection of necessary unavailable data to represent domains and indicators will provide the best chance at determining a group's resilience to climate events (regardless of spatial scale).

4. Climate Events and Resilience

In our consideration of the interdependence of humans and ecosystems in both vulnerability to and recoverability from climate events, we cannot ignore the interplay of natural systems and climate event risk as well as built environments with associated economic, social, and governance structures and climate event recovery. This set of intricate interactions shows that our survival banks on finding solutions to the vulnerability-recoverability nexus that are holistic and synergistic. Research approaches linking vulnerability and recoverability suggest that dynamic equilibrium for natural and built systems exists only when inflows and outflows are holistically considered and balanced [*Meadows*, 2008]. Hence, resilience (recovery from a perturbation) is the result of a complex set of feedback loops or behaviors that can "balance" the changes created by exposure to an event (in this case a climate event). The length of the delay to recovery may be the result of the interactions of these feedback loops representing environmental, economic, societal, and governance elements.

Increasingly, communities throughout the United States are examining their abilities to respond to and recovery from extreme climate events. Many of the indices described in our review focus on the point where vulnerability and recoverability intersect rather than how they are related. This relationship is critical for the development of a symbiotic and synergistic recovery from a climate disaster and to further permit adaptation for future climate events.

5. Proposed Conceptual Model Structure

Previously, the concepts of vulnerability and recoverability/resilience have been kept artificially separated through modeling conventions and differing schools of thought when, in reality, the concepts represent two sides of the same resilience coin. Using a scaled, proportional approach to the integration of these concepts will eliminate the need to classify characteristics of an area as contributing to either vulnerability or resilience. The combination of these five subindices, 11 domains, and 28 indicators are shown in a conceptual model for the climate resilience screening index (CRSI) in Figure 4. This model shows that all domains are entered without preexisting determinations of recoverability or vulnerability. Each domain is dynamic and able to move in either direction along the resilience scale depending on the characteristics of the place.

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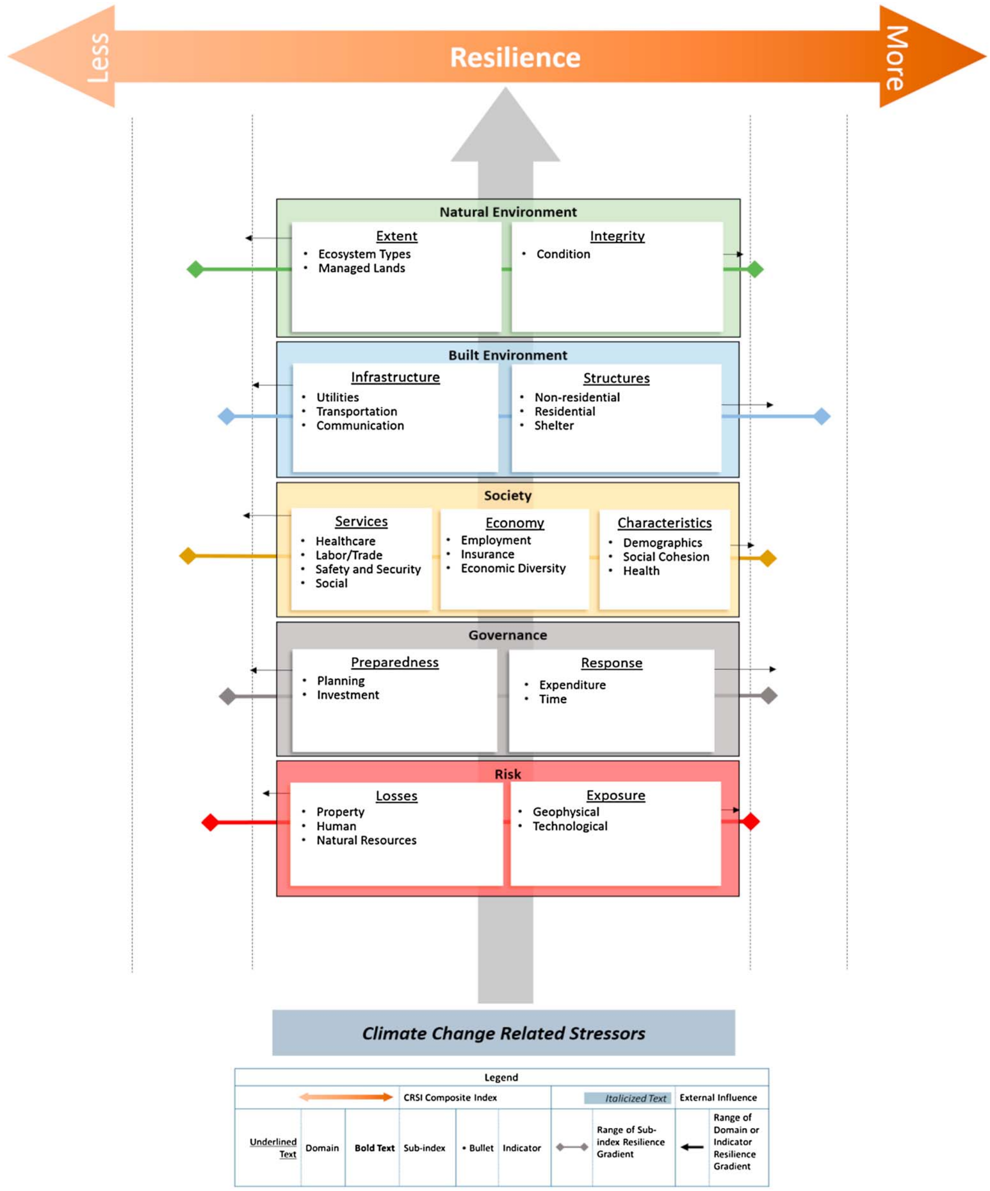

Figure 4. Conceptual diagram of the proposed CRSI development approach.

The model displayed here would utilize a place-based approach, using the county as a unit of analysis, and would be scalable dependent on data availability. The median values for each metric would set the theoretical center of the model from which county values are assessed. This will also allow for the ability to scale the model and define the extent used in subsequent analyses.

This index can be used to determine specific vulnerability while the remaining subindices all contribute some exacerbating factors for vulnerability but primarily contribute to aspects of recoverability. As depicted in Figure 4, the interactions of these five subindices result in resilience regardless of the spatial scale. This could be a user-driven calculation in the future, where the scale is determined based on the need of the end-user. In theory, this would allow spatial enumerations as small as blocks all the way up to states or EPA regions to be compared with respect to climate resilience. Model outputs could utilize a structure similar to the conceptual model as well in order to quickly visualize the domains in which a place excels or lags behind.

6. Conclusions

There is a growing use of the term "resilience" not only in research but also in planning, governance, and politics. This is a priori a positive phenomenon because it suggests that the relations between urban problems, sustainability, disaster risk management, and climate change have entered into the public discourse. It provides challenges to politicians and professionals, who are distinct from those managers and decision-makers associated with sustainable development. In addition, the multiple references in the scientific literature across different disciplines indicate the tendency of many communities to adopt transdisciplinary approaches to research. The development and application of the climate resilience screening index (CRSI) will advance the transdisciplinary aspects necessary to holistically address climate resilience. The authors intend to address the application of this approach to the counties of the United States in a subsequent manuscript which will detail the application process and the results. This future manuscript will provide results for all of the climate resilience domains and comparative scores for the index, domains, and indicators in two spatial forms—by county and by region of the United States.

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