An Integrative Approach to Conceptualizing Sustainable Resilience

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Vulnerability, resilience, and sustainability are three concepts commonly used in assessing the quality of a variety of systems. While each can be applied independently when performing risk analysis, there is growing interest across multiple disciplines in understanding how these concepts can be integrated when considering complex adaptive systems, such as communities. In this paper, we identify issues related to the use of these respective concepts in assessing complex adaptive systems, and describe how these issues may produce imbalanced results and maladaptive outcomes. We identify five critical areas where alignment and integration across concepts can lead to improved system assessment. As a result, we introduce a new paradigm, sustainable resilience, in which these concepts are integrated to enable alignment of adaptation and transformation strategies with desired resilience outcomes. This work provides the foundation for the development of an integrated assessment framework to help guide informed risk-based decision making for sustainable and resilient systems.

Keywords: Sustainable Resilience, Vulnerability, Integrative Framework, Transformation, Complex Adaptive Systems

Introduction

There is increasing focus on understanding individual and combined impacts of environmental stress, extreme events, and human development on communities and the environment. As collective understanding of the dynamic nature of human impacts on the environment and environmental impacts on human society has grown, greater effort has been placed on engineering systems that are able to maintain quality, withstand change, and minimally impact the surrounding environment. Vulnerability, resilience, and sustainability are three concepts that have emerged from ecological, engineering, and social science disciplines as criteria to meet these goals.

Each of these concepts is suited to assessing different aspects of system quality (e.g., exposure to harmful events, ability to resist disruption, expected lifetime of a current system state based on critical resources), each concept is typically utilized at different points in planning and decision making processes. Yet, these concepts ambiguously share many terms and attributes associated with a common foundation in risk assessment, management, and communication. Identification of gaps and linkages across each concept, and their relationships to the ability of current and future systems to adapt and/or transform are therefore needed (Adger, 2006; Bahadur et al., 2010; Upadhyaya et al., 2014; Bocchini et al., 2014; Minsker et al., 2015).

To date, there has been a paucity of literature devoted to how these concepts are used to assess dynamic system quality (Adger, 2006; Fiksel, 2006; Turner, 2010; Engle, 2011; Ahern, 2011; Miller et al. 2010; and Bocchini et al., 2014; Minsker et al., 2015). Moreover, while approaches for combining aspects of resilience and vulnerability (Cutter et al., 2008; Cutter et al., 2014; Frazier et al., 2014; Lam et al., 2015; Mayunga, 2007; Manyena, 2006), or resilience and sustainability (Ashley and Carney, 1999; Turner et. al., 2003; Wilhelmi and Hayden, 2010;

O'Connell et al., 2015; Minsker et al., 2015) frameworks have been developed, to our knowledge, a framework explicitly combining all three concepts based on critical evaluation of framework linkages and interactions has yet to be proposed.

In this paper, we review the individual concepts of vulnerability, resilience, and sustainability, as well as existing efforts to develop integrative frameworks. We then identify and illustrate critical linkages among concepts, and provide analysis of value added through strategic alignment. We then introduce a new concept to achieve this alignment that reflects the desired end-state for dynamic integrated system assessment, which we term "sustainable resilience." This work forms a necessary foundation upon which a framework for dynamic assessment of sustainable resilience can be formed. Critical concepts and terminology used in the analysis are italicized within the text and defined in the Appendix.

Background and Literature Review

Risk

Decision making under uncertainty is an inherent part of any *complex adaptive system*, where a range of outcomes are possible. In the context of this paper, we define a *system* as a collection of components that provide specific and related functions that are combined to serve a common purpose (Bossel, 2001). Across all lifecycle phases of social, engineered, or *coupled systems*, decisions are made that result in impacts across time and space, creating a set of dependent responses that ultimately affect quality and performance (e.g., the system's ability to serve society). The term *social-environmental system* is used in this paper to describe linkages between humans, human systems (engineered and/or social), and the surrounding environment (built and/or natural). This term is intended to include socio-technical systems, a term widely used within the literature. Our intent is to encompass linkages and interactions between humans, natural systems, engineered (built) systems, socio-technical (technology & infrastructure) systems, and socio-economic systems.

Risk differs from *uncertainty* through inherent association with the concept of harm and resulting consequences (Kaplan & Garrick, 1981). It can be argued that the concepts of *vulnerability*, *resilience*, and *sustainability* all fall under the umbrella of risk management as each involves the identification and characterization of potential performance degradation and mitigation opportunities to reduce negative consequences. To better understand goals associated with each concept and how they relate to varying applications of risk, a review of each concept is provided below.

Vulnerability

Vulnerability is described as the extent to which a system is likely to experience losses from a *hazard* (impactful event), and as such, it is a universally negative quality (Turner et al., 2003). *Vulnerability assessment* has evolved along two dominant tracks in the natural hazards community and the social science community. In the natural hazards literature, vulnerability employs a risk-hazard model, where vulnerability is defined as the combination of a risk factor and the potential for loss in the system at risk (Turner et al., 2003; Eakin & Luers, 2006). In the social science community, vulnerability traditionally focuses on inequities in *sensitivity* and *exposure* (social equity), resulting from social-structural characteristics such as socioeconomic and/or political status; governance; and community cohesion (Adger, 2006; Cutter et al., 2003; Turner et al., 2003; Eakin & Luers, 2006). Here, less emphasis is placed on physical damage incurred by a specific hazard while a greater emphasis is placed on identifying who is vulnerable and why they are vulnerable. Foundational application of the social sciences approach (Adger, 2006; Cutter 2003; Eakin & Luers, 2006) remains widely used in current applications within literature (Cutter, 2016a; Cutter, 2016b). In both cases (risk-hazard and social science applications), imbalanced assessment can occur through over-emphasis of either the physical or social aspects of vulnerability, leading to an incomplete understanding of system vulnerability.

A more recent approach to defining vulnerability attempts to merge both perspectives by defining vulnerability as the, “state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt,” (Adger, 2006). We defer to this definition, which includes three components: exposure, sensitivity, and *adaptive capacity*. Exposure is the magnitude and extent to which a disruption (hazard event) or stress is experienced, sensitivity is the expected degree of impact from a disruption or stress given exposure, and adaptive capacity is the ability to prepare for and respond to disturbance and is dependent upon the ability to effectively access and use necessary resources (Adger & Vincent, 2005; Adger, 2006; Engle, 2011).

Despite the breadth in definition, little consensus exists on the appropriateness of different methods for measuring or characterizing vulnerability across social-environmental systems. This is in part due to continuing challenges in the ability to operationalize different components of vulnerability and how to account for differences between short-term and long-term vulnerability (Engle, 2011; Gallopin, 2006; Fekete, 2012; Fussel, 2007; Eakin & Luers, 2006; Hinkel, 2011). For example, it has been noted that overlap exists between sensitivity and adaptive capacity, as an indicator of sensitivity at one time scale (e.g., poverty may be an indicator of sensitivity during an active emergency as fewer resources are immediately available to respond to the crisis at hand), yet may be an equally valid indicator of adaptive capacity at another time scale (e.g., poverty may also be an indicator of adaptive capacity as fewer resources are available to adequately prepare for future emergencies) (Frazier et al., 2014). Differences in operationalizing vulnerability are also obvious when considering the numerous variations in defining adaptive capacity, examples of which include coping capacity, coping ability, and capacity of response (Gallopin, 2006). In some cases, these terms refer to characteristics that exist before a harmful event occurs and impact outcomes in the short-term, while in others they refer to processes such as social learning that produces impacts in the long-term (Adger et al., 2004; Fussel, 2007; Gallopin, 2006; Keck and Sakdapolrak, 2013; Turner, 2003).

Vulnerability assessments are often used as a pre-event planning tool or for post-event analysis, and are typically conducted using indices that represent various attributes and properties of sub-systems or system components in order to evaluate exposure to harm and possible distribution of impacts. There are few examples of vulnerability assessment that adequately balance all aspects of social-environmental system components (e.g., human, engineered systems, social systems, natural systems) and consider their cross-scalar interactions (Engle, 2011; Adger, 2006; Fussel, 2007). Difficulties in addressing multi-scalar interactions may reflect the typical micro-scale lens employed in vulnerability assessments. While analysis at this scale can be a strength when identification of critical sub-systems/components or social justice issues within a system is needed, emphasis on the micro-scale can provide an incomplete picture of impacts at the system level (Miller et al., 2010). Current frameworks for vulnerability assessment do not adequately address dynamic temporal changes in vulnerability, critical *thresholds*, and/or multi-scalar interactions (Engle, 2011; Hinkel, 2011; Fekete, 2012; Miller et al., 2010; Frazier et al., 2014). As a result, imbalanced vulnerability assessment can provide discrepant and/or contradictory conclusions which may lead to adoption of inefficient and/or ineffective strategies to improve system quality and performance.

Resilience

The concept of *resilience* originates from ecological science, where it was defined as a system's ability to, "absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973). Resilience in this sense is a property that results in a system's level of persistence. A commonly accepted definition of resilience is the, "capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks" (Folke, 2006). This definition considers both system persistence and adaptability within the context of complex system interactions such as cross-scale dynamics, dependency, multiple equilibria, and feedback loops (Folke, 2006; Turner et al., 2003).

Recent definitions of resilience associated with social and economic systems incorporate the concepts of coping, adaptive, and transformative capacities (Engle, 2011; Keck & Sakdapolrak, 2013), and the ability to adapt or reconfigure to achieve strategic goals (Martin, 2012). For example, a community that is able to minimize physical flooding, has proactive emergency communication systems and sufficient emergency response infrastructure, and that is able to learn from flood events and take action to improve the outcomes of future flood events could be considered to be resilient. Doorn et al. (2018) go a step further and combine resilience with a capability approach that links social justice and well-being to infrastructure damage and recovery, highlighting interactions between social and physical coping and recovery processes. Resilience can also be viewed as a process that includes planning, preparation, monitoring, and learning to respond to change in order to achieve desired long-term goals (Godschalk, 2003; Ahern, 2011; Davoudi et al., 2012; Wilkinson, 2012; Desouza & Flanery, 2013; Sharifi & Yamagata, 2014; Arup and The Rockefeller Foundation, 2014) that are often associated with urban planning.

Among these resilience definitions are a number of common attributes: i) most refer to the ability of a system to absorb and adapt to disruptive events, ii) recovery from disturbance is considered a critical component, iii) some require a return to a steady or pre-disturbance state, while others allow for system degradation or the possibility of an enhanced or transformed state, iv) many include emphasis on *preparedness* and *recovery* activities (Hosseini et al., 2016; Koliou et al., 2018), and v) the attainment of resilience is often linked to achieving desired levels of system performance (Bruneau et al., 2003). In the case of social, engineered, or coupled systems, resilience is typically associated with attaining some combination of achieving social health and wellbeing and infrastructure/environmental stability and function (Keck & Sakdapolrak, 2013, Meerow et al., 2016a).

Defining resilience is an ongoing process as systems characterization and risk identification evolve. *Resilient systems* are also characterized by system attributes that impact different components of resilience, such as *robustness*, *redundancy*, *reliability*, preparedness, *rapidity*, risk, vulnerability, sustainability, and adaptive capacity (Bruneau et al., 2003; Rose, 2009; Keck & Sakdapolrak, 2013; Hosseini et al., 2016). The terms preparedness, rapidity, and *recovery* are often associated with community and infrastructure resilience, and are related to the ability to anticipate, plan for, and respond to disruption in ways that minimize injury and loss and allow for timely recovery of functions (Godschalk, 2003; Vale & Campanella, 2005; NIAC, 2009; Bozza et al., 2015; Minsker et al., 2015). Recovery itself is a complex term, especially for communities and associated infrastructure systems, where prevention of future loss and injury may require significant change or *transformation* involving multiple subsystems, objectives, and tradeoffs (replace, retreat, or relocate) rather than a return to pre-disturbance conditions (Vale, 2014). Uncertainty is also an important attribute associated with resilience, requiring an uncertainty-robust adaptation approach to manage lack of homeostasis and the need for flexibility when considering strategies for climate change (Wardekker et al., 2010).

Growing appeal and multiple definitions make resilience susceptible to criticism and point to a need for caution in its application. Davoudi et al. (2012) warn practitioners to carefully translate the use of resilience from one discipline to another and to avoid creation of a catch-all approach that is so malleable as to be “indefensible”. Meerow & Newell (2016b) also caution against a “one-size-fits-all” approach by emphasizing a need to question how resilience is to be applied, or more specifically, “resilience of what, to what, for whom, where, when, and why?” The nature and specificity associated with these questions is intended to avoid inconsistent, unintended, or maladaptive outcomes that can be associated with improperly scaled or incompletely informed decisions and associated trade-offs in planning processes to achieve resilience.

In contrast to vulnerability assessment, *resilience assessments* are often conducted in a dynamic way at multiple stages within a system planning and/or event response and recovery process, seeking to evaluate performance-based measures in response to systemic stress and disruption. Resilience assessments are often applied to relatively short-term events, one exception being the assessment of resilience to climate variability, which can cover a much longer temporal horizon. Complex coupled systems often require identification and use of indicators and metrics to represent specific performance objectives and use of statistical methods or network models to evaluate assessment outcomes (Baroud et al., 2014; Bozza et al., 2015; Linkov et al., 2014; Lam et al., 2015).

The exact nature of relationships between resilience, its multiple components, and various system attributes are often variable and not well defined. For example, Doorn (2017) provided a review of resilience in disaster management and found that different disciplines use varying definitions and relationships to describe resilience and vulnerability, and that distributive issues (e.g., access to resources, harmful impacts, etc.) are not well addressed in the literature, making it challenging to determine standards for social equity both before and after a disaster. As a result, difficulties can arise in aggregating measures across coupled systems where components or sub-systems may have differing levels of resilience, while taking into account the linkages between different system characteristics. Inadequacies in resilience assessment can lead to: 1) short-term solutions that give the appearance of resilience, 2) poor strategies for reducing the severity of anticipated impacts and inadequate recovery planning that can lead to rebuilding the same set of conditions that resulted in system failure in the first place, and 3) failure to effectively use available resources and adaptation strategies (Vale, 2005; Masterson et al., 2014). For this reason, it is not always desirable to return to a pre-disturbance state, but rather to consider achieving an altered or transformed state through incremental adaptation, partial transformation or complete transformation.

In today’s world, physical, social, and economic systems are increasingly interconnected, resulting in complex interactions, which impact system performance in the presence of disruption. Koliou et al., 2018 provides a timely review of applications in resilience assessment for a variety of complex system types. The review finds a general lack of resilience assessment frameworks that are able to consider the multi-functional dynamics of complex systems (natural, built, social, and economic components and their interdependencies), and states that attempts to aggregate results from single-system analyses has contributed to confusion and inconsistency in the collective ability to understand and apply concepts (Koliou et al., 2018). While static levels of resilience may appear high (based on immediate availability of resources for response and recovery), long-term resilience is driven by sustained levels of availability and access to resources needed to fuel adaptation/transformation strategies. Current definitions and analytical frameworks do not account for all of these aspects, resulting in potential discrepancies in the assessment of resilience to inform decision making for critical resource allocation before, during, and after a disruptive event (Hosseini et al., 2016; Minsker et al., 2015).

Sustainability

Much of current *sustainability* literature defers to the Brundtland Report definition of *sustainable development* that includes trans-generational (long-term) equity by requiring that development be able to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). The concept of recognizing present and future needs is related to understanding the interdependence between critical human-centric and ecological-centric resources (coupling), as well as overall social dependence upon both types of resources necessary to sustain development over time. In the literature, a sustainable social-environmental system is sometimes characterized as a system with the ability to provide sufficient resources to the human population without endangering the viability of the natural system, it is essentially concerned with addressing “threats to provisioning society and to maintaining life support systems,” (Turner, 2010) through management of critical resource capital. Critical resource capital, or s*ustainability capital*, must be managed strategically over appropriate spatial and temporal scales to ensure future viability (Berkes & Folke, 1998; Kates et al., 2001; Marcotullio, 2001; Fiksel, 2006; Dietz & Neumayer, 2007). This includes managing both risk and opportunity to provide desired outcomes and overall system performance (Pope et al., 2004).

In this sense, “capital” refers to the quality and abundancy of a critical resource (social, economic, or environmental) that may be available at a point in time (Alberti & Susskind, 1996; Pickett et al., 2004; Mayunga, 2007; Wilson, 2010; Bettencourt & West, 2010; Mori & Christodoulou, 2012; Hiremath et al., 2013; Vanegas, 2003). These can broadly be described as follows:

- *social* - people, skills, health, and broad governance (provision of services, political capacity, law, and justice, among others);
- *economic* - employment, income levels, market diversity, tax base, business growth, and internal/external funds, among others.; and
- *environmental* – (natural and built) air, land, water, food, energy, ecosystem health, facilities, and infrastructure systems, sub-systems, and supporting networks.

Sustainability seeks to achieve environmental equity, long-term allocative efficiency, and distributive efficiency (Bithas & Christofakis, 2006) across sustainability capital in order to maintain system viability and well-being. Issues of finite supply, non-substitutability, and tipping points are also encompassed in the concept of sustainability. The concept of “strong” sustainability prohibits substitution of one capital for another (e.g., economic growth for environmental health or social equity) (Finco & Nijkamp, 2001; Dietz & Neumayer, 2007), as opposed to “weak” sustainability, where some trade-offs are allowable in order to maintain a combined capital stock under general limits of growth and capacity (Nourry, 2008). Growth is ultimately limited by the availability of capital and the capacity for assimilation of waste through sinks across various systems (with overriding limitations imposed by planetary carrying capacity) (Berkes & Folke, 1998; Fischer et al., 2007; Rockstrom et al., 2009). Without sufficient quality and quantity of critical resources (e.g., skilled labor, money, water, land, energy, etc.), referred to herein as sustainability capital, or the ability to change to address deficits in sustainability capital, system quality may be challenged. An understanding of thresholds and limitations at various scales (global, regional, local) is necessary in order to manage and employ capital when and where it is needed to enable resilience through capacity for change (Folke et al., 2002; Folke et al., 2003; Longstaff et al., 2010; Engle, 2011).

The challenge in seeking and maintaining sustainability lies in the balance between trade-offs among capital and the ultimate risk of exceeding acceptable thresholds for consumption and degradation, resulting in the possibility of irreversible damage or failure (Moldan et al., 2012; Botero et al., 2015). Like resilience, sustainability (or more specifically, sustainable development) can also be viewed as a process, in addition to a normative state, and can require iterative steps of assessment, planning, monitoring, and re-assessment to achieve desired long-term goals linked to system integrity, livelihood sufficiency, opportunity, resource maintenance, and adaptation (Adger et al., 2005; Gibson, 2006; Rosales, 2011; Boyko et al., 2012). Recent planning goals to achieve sustainable cities have been developed within the U.S. and abroad (UN, 2015; NAS, 2016).

In contrast to traditional use of vulnerability and resilience assessment, *sustainability assessments* are typically carried out prior to system development and are not often reassessed throughout a system’s lifetime. Sustainability assessments typically focus on risk in terms of a system’s impact upon its critical resources (sustainability capital), in order to achieve a long-term balance between the availability (access to needed quality and quantities) of resources and the system’s ability to provide desired services to society. Assessments can be conducted proactively based on desired achievement of sustainability goals and objectives for a future system (reduce risk and associated consequences), or reactively to assess sustainability for existing systems relative to an established baseline and future goals/objectives. Timing of assessments can impact the degree of trade-offs that may be possible when considering impacts to different sustainability capital categories, with greater constraints placed on reactive assessments (Pope et al., 2004).

When used to characterize system quality, sustainability assessment without adequate consideration of changes to sub-system/component vulnerability and system resilience can lead to sub-optimal system performance (Minsker et al., 2015). Where specific applications of sustainability assessment may require that a system is optimized to reduce material flows, the same system may also require an increase in materials to achieve decreased vulnerability and/or increased resilience through protective measures such as increasing *robustness* and adaptability (Bozza et al., 2015; Ahern, 2011; Bocchini et al., 2014). This is especially true over time and under changing circumstances that may not have been fully anticipated, or may not be fully definable without a high degree of uncertainty (Linkov et al., 2014; Minsker et al., 2015), such as climate change. Current analytical frameworks do not adequately address these issues by broadening the scope and objectives to account for critical system properties such as its vulnerability and resilience that are not included in typical sustainability assessments (Bocchini et al., 2014). While sustainability is inherently multi-generational in scope, typical sustainability assessments offer only a snapshot in time related to a specific set of resource trajectories (Mori & Yamashita, 2015). In addition, current frameworks do not adequately address dynamic system changes and resulting sustainability impacts over time (Minsker et al., 2015). This does not allow for evaluation of long-term sustainability. Such limitations highlight the need for iterative and multi-scenario approaches to assessing system sustainability.

Adaptive Capacity

Each of the aforementioned concepts (vulnerability, resilience, and sustainability) are related to a system's ability to adapt and/or transform. The concept of adaptive capacity, as previously stated, is commonly understood as the ability to prepare for and respond to disturbance (Adger et al. 2004; Adger, 2006; Engle, 2011). This concept is less developed than the concepts of vulnerability, resilience, and sustainability, and not widely utilized by practitioners in the form of assessment techniques. However, it is gaining traction in social-environmental system assessment as it is commonly recognized as playing a vital role in both vulnerability and resilience concepts (Engle, 2011). In addition, it is widely recognized that the adaptive capacity of a system is dependent upon the resources available to that system, critically linking it to the concept of sustainability via availability and use of sustainability capital to affect positive change (Adger et al., 2004; Adger & Vincent, 2005; Engle, 2011; Turner, 2010). Whereas sustainability relates to the balanced management and interactions between forms of capital, adaptive capacity relates to the ability to effectively apply forms of capital to realize desired change (reduce harm, increase benefit), often through social structures and governance processes (Folke et al., 2002).

While the concept of adaptive capacity is not one of the primary concepts commonly used in complex system assessment today, it is implicit within any assessment oriented towards understanding the quality and performance of adaptive systems, and plays a key role in linking the three aforementioned concepts of vulnerability, resilience, and sustainability (Engle, 2011). Much work remains to be done to understand the nature of interactions between vulnerability, resilience, sustainability, and adaptive capacity, and how to avoid maladaptive outcomes over time and space (Romero-Lankao et al., 2016).

Used independently, each type of assessment discussed above produces a characterization of risk from an internal or external perspective over varying spatial and temporal scales that can be used to inform future actions to increase system quality and performance. However, when applied independently, they may not effectively or efficiently account for dynamic interactions across varying perspectives (impacts to systems or by systems), scales (temporal and spatial), and dependent systems (social, ecological, engineered, and coupled social-environmental). In recognition of limitations in using only a single concept to assess system quality and performance, efforts have been made to combine aspects of concepts with varied results. For example, the Disaster Resilience of Place (DROP) model (Cutter et. al., 2008), and SERV (Spatially Explicit Resilience-Vulnerability) model (Frazier et al., 2014) both integrate vulnerability and resilience yet lack robust consideration of sustainability. On the other hand, the Resilience Adaptation Transformation Assessment and Learning Framework (RAPTA) integrates concepts of resilience and sustainability yet does not explicitly account for vulnerability (O'Connell et al., 2015). While there are examples of frameworks that integrate two concepts explicitly and the third concept implicitly, to our knowledge, no framework has yet been described that explicitly accounts for all three concepts (vulnerability, resilience, & sustainability) with appropriate linkages to adaptive capacity, and associated interactions between concepts.

Materials and Methods

Evaluation of Concepts

A review of existing efforts point to a need to strengthen areas of perceived weaknesses in the ability to assess complex system quality absent consideration of all three assessment types. In this section, we examine these weaknesses in the context of suggesting areas of added value that could be produced by more comprehensive integration of the concepts. For the purpose of this discussion, we utilize the following definitions, (1) vulnerability is the likelihood of experiencing loss due to hazard as a function of exposure, sensitivity, and adaptive capacity; (2) resilience is the ability to resist disruption, recover, adapt, and/or transform given a hazardous event in order to maintain desired system performance; and (3) sustainability is the long-term ability to operate without failure through balanced management of critical social, economic, and environmental capital. Additionally, adaptive capacity is defined as the ability to cope with, recover from, and adapt/transform through effective use of available sustainability capital in response to a hazardous event at a point in time.

Table I below, presents a summary of strengths and weaknesses of individual concept application in complex systems assessment. Differences in perspective and scale across individual concepts produce strengths and weaknesses, and imply a need for further analysis regarding areas of convergence and divergence that help to identify where and how integration may lead to greater understanding of system quality. In the following section, we examine the relationships between concepts through comparison of goals, focal lens, scale (spatial & temporal), and metrics to identify linkages and interactions among concepts.

(Insert Table I)

Divergence, Convergence, and Interactions

Depending upon the framework used and the context of application, the concepts of vulnerability and resilience can be seen as inversely related, interdependent, or intersecting (e.g., vulnerability as a part of resilience or resilience as part of vulnerability) (Engle, 2011; Turner 2010, Lam et al., 2015, Gallopin, 2006; Bahadur et al., 2010). In some cases, a direct decrease in vulnerability is considered to be an approach to increasing resilience (Sahely et al., 2005, Cutter et al., 2008; Bahadur et al., 2010). Whereas some argue that resilience is a subset of vulnerability, and therefore increasing resilience can be seen as a way of decreasing vulnerability (Gallopin 2006, Turner et.al. 2003; Adger, 2006), others consider vulnerability a subset or factor in resilience metrics (Henry & Ramirez-Marquez, 2012; Baroud et al., 2014). In other cases, resilience is characterized as a component of, or contributor to, sustainability, where sufficient ability to resist disruption is required to ensure self-regulated operation over multiple generations (Fiksel, 2003; Mayer, 2008).

Increasing adaptive capacity is considered a means of both increasing resilience and decreasing vulnerability (Burch & Robinson, 2007; Engle, 2011; Romero-Lankao et al., 2016). Through “sustainability science,” resilience and vulnerability are regarded in a manner which implicitly links adaptive capacity to the availability and effective use of resources (Turner, 2010). While it is sometimes assumed that increasing resilience and/or decreasing vulnerability will increase sustainability and vice-versa, this is not necessarily the case. The focal lens of each concept, if improperly balanced, can lead to superficial consideration of related concepts and a failure to examine trade-offs, resulting in seemingly competing or misaligned goals and unsustainable outcomes (Mori & Yamashita, 2015).

In addition, dynamic environmental conditions, such as changes in climate, resource availability, and underlying control variables that impact system risk, lead to increased uncertainty in maintaining long-term resilience and sustainability. A system’s ability to remain viable in the long-term is a function of its ability to adapt over time to changing circumstances. In this respect, system performance needs to be re-examined within and across interdependent systems using not only averages, but with consideration of extremes, infrequent events with severe consequences

(Minkser et al., 2015). Whereas a conventional sustainability assessment may seek to minimize resource consumption in the development and operation of a system, this effort can undermine essential components of robustness and redundancy that are critical to resilience. Likewise, a conventional vulnerability or resilience assessment may not assess impacts to critical resources at spatial and temporal scales necessary to identify possible shortfalls in future availability of resources needed to support sustainability and fuel adaptive capacity (Mori & Yamashita, 2015). Analysis across all three concepts, perspectives, and scales is necessary to determine sufficiency in resource use and restoration/replenishment, as well as trends in increasing community performance over time (Milman & Short, 2008; Upadhyaya et al., 2014).

We assert that improved understanding of the nature of linkages and interactions is critical to enabling strategic integration of concepts, rather than a simple combination of terms. A detailed understanding of the interactions between concepts can highlight areas where a strategic approach to balanced integration and alignment of vulnerability, resilience, and sustainability goals may lead to an improved method for assessing the performance of any complex system (including communities), as well as improved ability to strategically build adaptive capacity, thereby strengthening long-term sustainability and resilience. The review of in-practice and conceptual literature on vulnerability, resilience, and sustainability presented earlier reveals at least five critical areas where conceptual interactions exist between assessment types: goals, focal lens, scale (spatial & temporal), and key measurement and practice terms. Table II presents a comparison of each concept across these critical areas.

From examination of the Conceptual Definition Terminology and Key Measurement and Practice Terms in Table II, it can be seen below that economic considerations (cost, effectiveness, efficiency) are common across the concepts; considerations of equity-related diversity and susceptibility are common across sustainability and vulnerability concepts; aspects of system performance such as robustness, reliability, and thresholds are common across sustainability and resilience concepts; the abilities to cope/resist and adapt in response to disruption are key components of both vulnerability and resilience; and sensitivity is a common concern (although at different levels) across all three concepts. Comparison of the scale of assessment indicates that shared consideration of the ability to cope/resist or adapt across vulnerability and resilience occurs at the component-scale for vulnerability, while resilience is reflective of coping/resisting and adaptation capability within and across linked systems. In addition, terms such as exposure and sensitivity can be seen to be key components of conceptual definitions of vulnerability, but not of resilience. However, measurement of sensitivity and exposure are common in resilience assessment, suggesting that the conceptual components of resilience are dependent on exposure and sensitivity. Consideration of terms such as resourcefulness and preparedness in vulnerability and resilience assessment imply that levels of coping/resisting and adaptive capacity over time depend on availability of sustainability capital, where long-term coping and adaptive capacity are dependent on the equitable distribution of resources over system lifetimes or generations.

(Insert Table II)

From the areas of divergence and potential linkages across concepts presented in Table II, we further identify specific areas where *strategic* integration of concepts can be expected to result in greater understanding of system quality over time, which we refer to as “value-added” in Table III. A summary of areas of value-added through focused integration of concepts, time-scales, systems, and resources is provided in **Error! Reference source not found.** below.

(Insert Table III)

Conceptual Linkages & Interactions

While the exact nature of the linkages and interactions between individual assessment types is currently debated, it is evident that causal relationships are present at the sub-system/component and system-wide level in relation to measurements for vulnerability, resilience, and sustainability over time. Conceptual linkages and interactions identified in earlier tables (I-III) are further illustrated in **Error! Reference source not found.** below.

(Insert Figure 1)

Overlapping areas indicate strong interdependence between primary and contributing concepts (e.g., adaptive capacity is a key component, or contributing concept, to both vulnerability and resilience). Primary concepts are represented by bold font. Dashed arrows indicate interdependence between concepts. For example, the quality and availability of sustainability capital (and ability to harness it to create change) impacts adaptive capacity. In turn, as resources may be utilized to create change, sustainability capital may also be impacted based on the degree of utilization and impacts to capital stocks. Over-utilization or lack of balanced management can render sustainability capital inadequate or inaccessible, thereby impacting vulnerability, adaptive capacity, and system resilience to varying degrees. Areas within the blue background refer to dynamic interpretations of concepts, while those outside refer to static interpretations of vulnerability and resilience that exist at a given point in time. The static state of vulnerability has a direct impact upon the static state of resilience within a system, and these static states contribute strongly to dynamic levels of system resilience. Changes in dynamic states are realized over time (through adaptation strategies, or lack thereof) via changes in and interactions between sustainability capital, vulnerability, and adaptive capacity as described below.

Within social-environmental systems, vulnerability assessment is typically applied to the component/sub-system scale of analysis (Miller et al., 2010). While resilience assessment is sometimes carried out for smaller scales of analysis, within the social-environmental system literature resilience assessment is typically conducted at the system-wide scale (Miller et al., 2010). Vulnerability and resilience are evaluated in both static and dynamic contexts in the literature (Cutter et al., 2008; Gallopin, 2006; Frazier et al., 2014).

Static characterization of vulnerability, termed here as *contextual vulnerability* in Figure 1, is defined as a pre-existing/current state of the system that takes into account exposure, sensitivity, and existing plans or capabilities that improve the effectiveness and range of actions available in response to a hazardous event (Cutter et al., 2008; Gallopin, 2006; Turner, 2003). This static form of adaptive capacity is herein referred to as *anticipatory coping capacity*, a component of contextual vulnerability (Figure 1). The resilience counterpart to contextual vulnerability is termed the *ability to resist systemic disruption* (Figure 1). This ability is based on the expected level of impact to critical sub-systems/components given their contextual vulnerability and interactions between those components that result in a systemic impact, where the overall system ability to either resist or succumb to disruption is also dependent on critical system performance thresholds.

As contextual vulnerability includes consideration of exposure, sensitivity and, through anticipatory coping, adaptive capacity, it can be deduced that the ability to resist systemic disruption is also dependent on these components (although considered at a different scale and in reference to performance thresholds). Since the ability to resist systemic disruption is a subset of resilience, this suggests that resilience is also dependent on exposure, sensitivity, and anticipatory coping capacity. These relationships imply that the concepts of vulnerability and resilience are also interdependent, and as formulated, are composed of the same basic building blocks. Despite this, differences in the scale, resolution, and unit of comparison that define the lenses of vulnerability and resilience mean that these concepts are not simple inverses of each other.

In addition, both vulnerability and resilience are dependent upon sustainability capital and its ability to promote or constrain adaptive capacity through availability and effective use of critical resources. The quality and quantity of capital on hand at any time can impact the ability of a system to harness needed capital in anticipation of, preparation for, or recovery from disruption. Therefore, adaptive capacity essentially functions as a moderator in determining levels of vulnerability and system resilience through availability of sustainability capital needed to realize change (Engle, 2011).

Lastly, sustainability is seen to be dependent upon the ability of the system to resist systemic disruption, recover, adapt, and transform, which we define as resilience, as these abilities directly impact deposits and withdrawals from sustainability capital; suggesting that sustainability and resilience are interdependent. Sustainability is also seen to be dependent upon vulnerability, as hazard impacts not directly related to system performance are still expected to directly influence deposits and withdrawals from sustainability capital. This again suggests that sustainability and vulnerability are interdependent.

Sustainable Resilience

In understanding and assessing the quality of complex adaptive systems over time, with the aim of reducing adverse impacts (disruption) to the system over its lifetime, we suggest resilience as the focal point for assessment integration. This does not presume that one concept is more important than another; rather it requires consideration of balance and alignment across concepts to achieve the capacity for long-term resilience. The evaluation of concepts and illustration of linkages and interactions as developed and presented (Figure 1), lead us to conclude that changes in sustainability capital and sub-system vulnerability can increase or decrease system-wide resilience over time through moderation of adaptive capacity.

As it is currently difficult to measure changes in adaptive capacity over time across complex systems, we propose that it is therefore critical to monitor significant shifts in both sustainability capital and sub-system/component vulnerability over time, and in conjunction with development and implementation of adaptation/transformation strategies in order to assess, and ultimately manage, current trends and possible future trajectories for system resilience. Given the discussed conceptual linkages and the suggested use of resilience as a system assessment focal point, we define *sustainable resilience as the ability of a system to maintain desired system performance by changing in response to expected and unexpected challenges over time, while simultaneously considering intra-system and inter-generational distribution of impacts and sustainability capital.* Vulnerability is represented within this definition by consideration of the intra-system distribution of impacts that result from varying levels of vulnerability within the system over time, and sustainability is represented by consideration of distribution of sustainability capital over the life of the system.

Discussion

Critical areas of interaction exist between vulnerability, resilience, and sustainability that suggest the need for an integrated assessment framework to better understand and measure the quality of complex adaptive systems. However, current literature does not provide a solid foundation on which to base integration of these concepts or an obvious focal point for assessment. In response to this need, we provide an analysis of linkages and dependencies between the concepts of vulnerability, resilience, and sustainability and their relationship(s) with adaptive capacity, and identify the value added that integration of concepts might provide to system assessment processes. We further develop the concept of sustainable resilience to better communicate the need for balance and alignment across concepts to achieve the capacity for long-term resilience.

A detailed framework to assess vulnerability, resilience, and sustainability in an integrated manner that can be adapted to fit a variety of systems and ultimately operationalized has yet to be described in the literature. We suggest that an integrated framework for assessing sustainable resilience based on the linkages and interactions between the concepts of vulnerability, resilience, and sustainability, as described in this paper, could fill this gap and result in improved ability to:

- Identify or anticipate significant changes in, or the need to alter, availability of sustainability capital through management practices (maintenance, withdrawals, and investments) over time;
- More effectively use sustainability capital to reduce critical sub-system vulnerability and improve resilience outcomes through successive monitoring and/or scenario development aimed at evaluating the impact of adaptation strategies; and
- Identify or anticipate when to consider system transformation (adaptation is no longer feasible, and transformation strategies may lead to new systems and objectives).

To further advance the concept of sustainable resilience, forthcoming work will describe a dynamic assessment framework for sustainable resilience that can be adapted to fit a variety of systems and that adds value to overall system characterization through recognition of key interactions across assessment types.

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Appendix

Term	**Definition**
Ability to Resist Systemic Disruption	Degree to which hazard-induced impacts to the system do not result in disruptions in system service (a static state); the ratio of impacts to performance measure thresholds.
Adaptation	An incremental change undertaken either in anticipation of stress, or in response to stress, intended to improve survivability or quality.
Adaptation/Transformation Strategies	Actions (collective or independent) developed by decision makers as part of an assessment/planning process that are intended to reduce anticipated injury and loss to a system; transformation strategies can result in a new system definition.
Adaptive Capacity	Also called adaptability, the ability to cope with, recover from, and adapt/transform through effective use of available sustainability capital in response to a hazardous event at a point in time.
Anticipatory Coping Capacity	A subset of adaptive capacity that specifically refers to conditions existing prior to a hazardous event; the ability to reduce the impact of a hazardous event via preparation/readiness. Includes planned individual actions, community support systems, or system-wide policies and programs in-place at the time of a hazardous event that improve the effectiveness and range of actions available in response to the event.
Complex Adaptive Systems	Systems characterized by multi-scalar and cross-scalar dynamics, feedback loops, interactions, that exhibit changes in system function and/or objectives over time.
Coupled Systems	Systems that are linked such that a system(s) may depend on one or more systems whereby the quality or fate of any individual system is shared or impacted by others.
Contextual Vulnerability	Extent to which a system is likely to experience losses from some hazard based on conditions at a specific point in time immediately prior to the onset of the hazard (a static, pre-existing or current state); a function of exposure, sensitivity, and anticipatory coping capacity.
Coping Capacity	Also called capacity of response, adaptive capacity, and coping ability. Refers to the ability to absorb shock and respond to immediate threats.
Economic Capital	Money, property, credit, markets, other forms of financial capital that provide currency for economic activity and allow for transactions needed to ensure system viability and insure against risk.

Environmental Capital	Includes both built and natural resources (sometimes called natural capital), refers to renewable and non-renewable natural resources (air, water, land, vegetation, wildlife, energy) essential for human survival and economic activity. Most are non-substitutable (e.g., the atmosphere cannot be replaced). Non-renewables includes fossil fuels, mineral deposits, extinction of species, etc. Also includes engineered/built structures and supporting infrastructure systems.
Exposure	The magnitude (severity) and extent (in terms of spatial extent and temporal duration) of a hazard.
Hazard	A threat to a system, either a perturbation, disturbance, or stressor.
Preparedness	A state of readiness that requires anticipation, planning, and actions needed to support response and recovery from disturbance.
Rapidity	Speed of recovery from a state of disturbance to an acceptable level of performance that can be similar to the pre-disturbance or a new state.
Recovery	A time in which a system attempts to restore system function immediately following a hazard.
Redundancy	Existence and availability of duplicate or alternate components within a system, such that if one component fails, an alternate can perform its function to prevent systemic disruption or failure.
Reliability	Ability to operate without failure under specified conditions.
Resilience	Ability of a system to resist systemic disruption, recover, adapt, and transform given a hazardous event in order to maintain desired performance.
Resilience Assessment	Evaluates/measures system performance with respect to failure scenarios, resulting impacts, time to achieve recovery, and associated costs using quantitative and semi-quantitative methods; it can be applied at multiple scales.
Resilient systems	Systems that possess physical, social, and organizational characteristics (both natural and designed/built) that allow the system to minimize systemic performance disruption given a hazard scenario, recover rapidly and effectively following a hazard scenario, or transform in response to a hazard in order to provide an acceptable level of service to society over the life of the system.
Risk	Occurrence of an event with an associated probability that results in a set of consequences.
Risk Appetite/Risk Tolerance	The amount of risk of adverse impacts that a system is willing to accept, usually as part of a trade-off with some other expected gain (e.g. financial).
Robustness	Ability to operate without failure under changing or adverse conditions (tests bounds of reliability).

Sensitivity	Innate physical characteristics and/or social structures that influence the degree to which impacts will be suffered given a certain level of hazard exposure.
Social Capital	Also called human capital, refers to the networks and relationships among people that enable society to function (e.g., community groups, associations, education, welfare, communication, law, government, policy, among others).
Social-Environmental System	Complex adaptive systems that are subject to multi-scalar relationships between the system, sub-systems, and external systems and where interactions between physical and non-physical factors are common. Related terms include: Coupled Human-Environmental System, Social-Ecological System, and Coupled Human-Natural System.
Strategic	Designed or planned to serve a purpose or intent through identification and alignment of long-term goals and objectives, and the means of achieving them.
Sustainability	Ability to operate without failure by achieving balance across availability and performance of critical resources (social, environmental, and economic) such that negative impacts to the environment are reduced while positive impacts to society and economy are maintained at an acceptable level both now and into the future.
Sustainability Assessment	Evaluates/measures current and projected health (availability and performance) of critical social, environmental, and economic resources needed in order for a system to function and survive using quantitative and semi-quantitative methods; it can be applied at multiple scales.
Sustainability Capital	The set of social, economic, and environmental capital that supports the existence of a community.
Sustainable Development	Development that maintains a desired level of system performance without compromising trans-generational equity in the availability of three key resources: social, environmental, and economic capital.
Sustainable Resilience	Ability of a system to maintain desired system performance by changing in response to expected and unexpected challenges over time, while simultaneously considering intra-system and inter-generational distribution of impacts and sustainability capital.
System Objective	A primary goal of the system as defined by the purpose of the system.
Systemic Disruption	Situation in which a system performance measure no longer provides an acceptable level of service.
Systemic Failure	Situation in which multiple system objectives are severely disrupted or irreversibly compromised.
Threshold	Value delineating between acceptable and unacceptable performance of a system objective.

Transformation	Change from an existing state to a new state through gradual transition (incremental adaptation) or abrupt transition such that the original system objectives are significantly altered.
Uncertainty	The range of possible values (multiple possible outcomes) within which the true value of a measurement lies. Various methods can be used to incorporate uncertainty into decision making process.
Vulnerability	Extent to which a system is likely to experience losses due to a hazard; a function of exposure, sensitivity, and adaptive capacity.
Vulnerability Assessment	Evaluates/measures levels of exposure, sensitivity, and adaptive capacity of critical system parts, components, or sub-components to determine the potential for loss related to a hazardous event using quantitative or semi-quantitative methods.

Table I: Strengths and Weaknesses (Gaps) of Individual Concept Application in Complex Systems Assessment

	Strength of Individual Concept	**Weaknesses (Gaps) in Current Application**
Vulnerability	Identification and assessment of sub-system/component: • Risks • Weakest points • Means to reduce severity of harmful impacts to specific sub-systems/components within current system constraints	• Balance across social-environmental components (human, engineered systems, social systems, natural systems, among others) • Consideration of interactions with and impacts on, sustainability capital and long-term viability • Sub-system/component interactions with system-wide performance and quality, particularly in relation to critical thresholds
Resilience	Identification and assessment of system-wide: • Performance related risks • Plans for reduction of harmful impact and severity • Recovery and adaptation strategies • Transformation needs associated with system operations	• Balance across social-environmental components • Consideration of sub-system/component level variations and their impact on system-wide performance and quality over time • Consideration of impacts on sustainability capital resulting from implementation of adaptation or transformation strategies and resulting changes in adaptive capacity
Sustainability	Identification and evaluation of multi-scalar critical resource capital: • Deficiencies and/or opportunities • Long-term system-wide viability and wellbeing	• Consideration of critical system and sub-system/component properties given hazardous event scenarios • Consideration of dynamic system changes over time, including the impact of adaptation or transformation strategies

Table II: Vulnerability, Resilience, and Sustainability Assessments: Conceptual Linkages and Interactions

	Focal Lenses	**Goals**	**Spatial and Temporal Scale**	**Conceptual Definition Terminology**	**Key Measurement and Practice Terms**
Vulnerability	• What can happen to the system? • What is the impact to the system? • How equitably are the impacts distributed?	Mitigate impacts to the system and improve survivability and/or well-being of entities within the system under the influence of stress and/or shock.	Spatial: Micro (sub-system/ component). Temporal: Short to mid-term.	• Adaptive Capacity • Coping/Response • Exposure • Sensitivity	• Cost • Density • Diversity • Extent • Duration • Effectiveness • Efficiency • Preparedness • Resourcefulness • Susceptibility • Impact
Resilience	• How did the system respond? • How will the system recover?	Maintain system performance and functionality in the presence of change, minimize periods of disruption, and recover as well as adapt or transform.	Spatial: Meso (system-wide). Temporal: Mid-term (operational lifetime).	• Absorb/Resist/Cope • Recover • Adapt • Transform	• Cost • Effectiveness • Efficiency • Exposure • Rapidity • Threshold • Performance • Coping/Response • Redundancy • Reliability • Resourcefulness • Robustness • Sensitivity
Sustainability	• How will the system impact its surrounding environment (across social, economic, and environmental systems and sub-systems)? • Will impacts to critical resources modify system viability?	Identify and manage impacts to connected resource systems and sustainability capital in order to maintain indefinite system viability and well-being.	Spatial: Meso (system) with macro (beyond system boundaries) connectivity. Temporal: Long-term or strategic (life-time and beyond).	• Equity • Long term resource availability (in terms of social, economic, and environmental capital) • Resource quality and quantity	• Access • Cost • Diversity • Effectiveness • Efficiency • Redundancy • Reliability • Resource Demand • Resource Supply • Robustness • Sensitivity • Susceptibility • Performance • Threshold

Table III: Areas of "Value-Added" through Focused Integration of Concepts, Time-Scales, Systems, and Resources

	Gaps (from Table 1)	**"Value-Added" through Integration to Address Gaps**
Vulnerability	• Balance between social-environmental components • Consideration of interactions and impacts on sustainability capital and long-term viability • Consideration of sub-system/component interactions with system-wide performance and quality, particularly in relation to critical thresholds	• Greater consideration of ecosystem and physical infrastructure effects • Greater consideration of constraints on adaptive capacity imposed by sustainability capital • Improved consideration of threshold conditions; • Improved consideration of impacts to system-wide performance • Improved consideration of impacts to system sustainability capital
Resilience	• Balance between social-environmental components • Consideration of sub-system/component level variations and their impact on system-wide performance and quality over time • Consideration of impacts on sustainability capital resulting from implementation of adaptation or transformation strategies and resulting changes in adaptive capacity	• Greater consideration of socio-economic and socio-political effects • Improved understanding of how to reduce severity of harmful impacts • Improved identification and consideration of sub-systems/components critical to maintenance of system-wide performance • Improved identification of adaptation and/or transformation strategies that can be effectively implemented • Improved consideration of effects on system sustainability capital in order to maintain long-term system viability
Sustainability	• Consideration of critical system and sub-system/component properties given hazardous event scenarios • Consideration of dynamic system changes over time, including the impact of adaptation or transformation strategies	• Greater consideration of changes in the availability of sustainability capital • Improved consideration of effect of sustainability capital on adaptive capacity

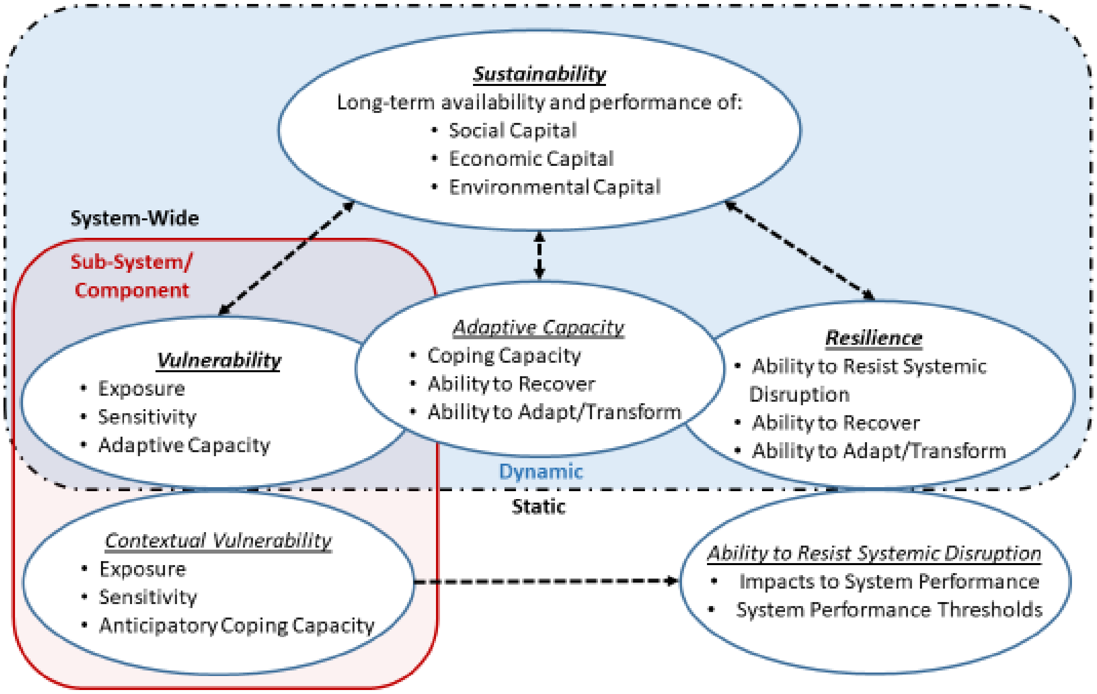

Figure 1: Assessing System Quality - Conceptual Linkages and Interactions