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Article

Resilience Attributes of Social-Ecological Systems: Framing Metrics for Management

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Abstract: If resilience theory is to be of practical value for policy makers and resource managers, the theory must be translated into sensible decision-support tools. We present herein a set of resilience attributes, developed to characterize human-managed systems, that helps system stakeholders to make practical use of resilience concepts in tangible applications. In order to build and maintain resilience, these stakeholders must be able to understand what qualities or attributes enhance—or detract from—a system's resilience. We describe standardized resilience terms that can be incorporated into resource management plans and decision-support tools to derive metrics that help managers assess the current resilience status of their systems, make rational resource allocation decisions, and track progress toward meeting goals. Our intention is to provide an approachable set of terms for both specialists and non-specialists alike to apply to programs that would benefit from a resilience perspective. These resilience terms can facilitate the modeling of resilience behavior within systems, as well as support those lacking access to sophisticated models. Our goal is to enable policy makers and resource managers to put resilience theory to work in the real world.

Keywords: resilience; resiliency; metrics; social-ecological systems; adaptive capacity; thresholds

1. Introduction

What makes a system resilient, and how can we manage for this condition?

In order to build and maintain resilience, managers must be able to understand what qualities or attributes enhance—or detract from—a system's resilience. We present, herein, a set of resilience attributes that enable policy makers, program managers, and stakeholders in collaborative initiatives to make practical use of resilience theory in understanding and managing their systems of interest.

We offer these resilience attributes as a basis for exploring and enhancing a system's resilience; they can be employed by leaders within a system, collaboratively by stakeholder groups, and by those having responsibility for subsystems within the whole. It is intended to enable stakeholders at all levels of a system, including the subsystem and component levels, to readily assess and improve the resilience of their part of the whole. It is also intended to promote, through application, a basic understanding and enduring awareness of resilience concepts and their role in system function.

These standardized resilience terms, from which metrics can be derived, can be incorporated into resource management plans and decision-support tools to help managers assess the current resilience status of their systems, gauge progress toward goals, make rational resource allocation decisions, justify funding choices, and enable training and unity of purpose across programs. The resilience attributes can also facilitate deeper investigations of resilience through ongoing efforts to model system behavior, and more importantly, they provide an approachable set of terms for non-specialists to incorporate into plans and programs lacking access to (or the desire to use) sophisticated models. Our intention is to provide policy makers and resource managers practical access to resilience theory for work in the real world.

It is important to clarify terminology up front. Much research has been performed in recent decades regarding resilience theory, and there are competing definitions for "resilience." One definition of resilience is the amount of disturbance a system can resist or the speed with which it returns to equilibrium. This definition of "engineering resilience" [1] is useful for describing closed systems, but many systems are not closed, limiting the usefulness of this approach.

Business leaders may think of resilience as "the capacity of an enterprise to survive, adapt, and grow in the face of turbulent change" [2]. However, current best practice in business and government usually consists of optimizing the production and delivery of goods and services [3]. Pursuing efficiency often requires tight control of a system's elements in isolation to create a steady "maximum sustainable yield." This approach is not necessarily sustainable in unpredictable, "open" systems that must adapt to a wide range of external perturbations—that is, most systems we find ourselves working within and attempting to manage.

Natural resource managers observe that ecosystems adapt, survive, and thrive despite a wide range of stresses and disruptions. Systems that are characterized by uncertainty and unpredictability appear more tractable when examined from an ecological systems perspective. It should be noted, though, that "natural" systems do not operate without human influence (even the most remote ecosystems feel the effects of climate change, industrial pollution, and aerosol-induced ozone depletion), and "human" systems do not function unaffected by the natural environment. This complex interconnectedness of humans and their environment is embodied in what are called social-ecological systems, or SESs [3]. For the purposes of this paper, an SES may be of any size, complexity, origin, or purpose, each with its own unique, highly varied linkages. An SES may consist of a community and the commercial, industrial, agricultural, water and energy supply, and other ecosystem services upon which it depends. Scaling down within that community it might be the local fishing industry and the fishery upon which it depends, or a factory and the workers, managers, suppliers, consumers, and resources and waste disposal associated with that factory.

We are concerned herein with the ways humans can assess and affect the resilience of an SES. For that purpose, we have oriented our efforts to satisfy the needs of people who normally focus on the systems, not on resilience concepts. In this context, resilience has been defined as the capacity of a linked SES to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity [1,3–6]. How much disturbance can the system—people, infrastructure, resources, and environment—accommodate while still maintaining its basic structure, capabilities, and capacity to function? How far can it bend and adapt without breaking? It is this definition we use as a basis for describing resilience attributes of systems in order to manage for system resilience.

Systems often fail in unpredictable ways, but resilient systems continue to function despite the challenges. Planning assumptions do not always hold true, and planners often fail to ask how well the system will function in the face of large, unexpected challenges, or the accumulation of many smaller stresses; these include market failures; geopolitical and demographic shifts; resource shortages (e.g., water, fuel, fertilizer, minerals); epidemics; climate change; and technology disruptions [7,8]. Retention of the SES identity is a concern since an SES can exist in alternate regimes or "stability domains," some less desirable than others. There are thresholds that, once passed, invite different system feedbacks leading to changes in function and structure [1,3,5,9]. Social-ecological systems can sometimes get trapped in very resilient but undesirable regimes. Adaptation may not be possible, and escape may require significant energy to cause change [10]. Thus, "the more resilient a system, the larger the disturbance it can absorb without shifting into an alternate regime" [5]. Being able to understand which resilience attributes of a managed SES need attention is an important first step toward avoiding undesirable thresholds, absorbing shocks, mitigating disruptions, and managing transitions.

The Need to Translate Theory into Practice

Resilience theory provides a powerful, holistic paradigm for understanding system dynamics. And there appear to be a number of conceptual strategies for enhancing resilience within a system. Some strategies involve (1) manipulating an important system variable or "reshaping the basin of attraction or stability domain" to reduce the odds of breaching thresholds [6,11–13]; (2) moving the "ball" away from the walls of the basin (moving the system away from a threshold) [6,14]; (3) understanding and manipulating the focal system's position within the Adaptive Cycle [3,15,16]; (4) manipulating factors at a different scale (or in a connected system) to increase system resilience at the focal scale (panarchy) [12,14,16,17]; (5) assessing the system for strengths and vulnerabilities based on attributes of system resilience and work to eliminate weaknesses. All of these strategies hold promise, and there are no doubt other strategies yet to be proposed. However, if it is to be of practical value for policy makers and resource managers, the theory must be translated into sensible decision-support tools universally applicable across large and small systems and enterprises. Towards that end, option five appears to be a direct, less complicated, and administratively tenable method suitable for those who want to incorporate resilience management into strategic planning as well as for those who do not wish to rely upon consulting experts, modelers, and large budgets.

As noted by Fiksel, "There is a great need for operational definitions and metrics for sustainability and resilience in economic, ecological, and societal systems" [2]. The resilience attributes presented herein are in answer to that need, providing a means for applying resilience concepts in tangible applications. Discussion of the theoretical underpinnings of these resilience attributes and the methodology and results of a resilience assessment based on the system attributes will be the subject of forthcoming articles; the focus of this article is to provide useful information for the non-specialist to apply to systems or programs that they manage and that would benefit from a resilience perspective.

Senior federal agency decision-makers have called for the means to instill and manage resilience in their programs; frustrated with inadequate, incompatible, and uncoordinated management policies, strategies, and tools that cannot accommodate resilience analysis, they have openly sought resilience metrics that would enable prioritization of activities and allocation of resources [7,18–20]. For example, the National Defense Industrial Association publishes each year the top issues it recommends DoD and the defense industry give their greatest attention. In its 2013 edition, it cites energy security as its third of eight issues, and specifically states that:

> "Energy resilience metrics should be part of the overall performance metric, and should be considered in requirements development and acquisition processes. This shift in emphasis from assuring supplies to assuring mission preparedness will complement and reinforce the mandate that mission performance takes priority over energy consumption. This new focus will also ensure future planning addresses not just energy supplies, but actual mission performance for the widest range of circumstances."

NDIA concludes with the following recommendation:

> "Despite the challenge to transition to an energy strategy that incorporates resilience and adaptability to evolving conditions given planned budget constraints, shifting mission priorities, and a need for flexibility in a changing global energy reality, DoD should consider making resilience a focus for energy security" [21].

This concern for defined attributes and metrics is understandable: Managers must monitor and measure what they manage. Since data collection and analysis is expensive, it is important to define the properties of resilience so that monitoring and assessment can be appropriately targeted. And just as important, this must be an integral component of the prevailing strategic management framework—Vision, Mission, Goals, Objectives, *Metrics*, and Milestones—that agencies and organizations use to set their program agendas.

Translating theory into practice, however, must yield terminology suited to the community of interest, in this case the SES stakeholders. Indeed, Gunderson and Folke have stated that "one of the major unanswered themes [is] the gap between science and policy that seems to be widening in many places.

In more practical or basic terms, what is the relevance of resilience scholarship to practical issues?" [16]. That scholarship must meet the needs of those working with real-world systems and aligned with their functional perspectives. "Expert solutions may maximize something, but they rarely maximize legitimacy" [11]. For stakeholder groups collaborating in initiatives to enhance resilience, it is preferable to have a user-friendly, practical method for communicating intent, translating intent into goals and objectives, and planning implementation activities rather than to rely upon a "black-box" approach. As such, we have focused on the synthesis of terms and definitions appropriate for those whose main concern is their system, not resilience concepts.

2. Resilience Attributes

Social-ecological systems appear to share attributes by which resilience can be characterized and assessed. We have investigated which system attributes relate specifically to the ecological definition of resilience, asking, "What attributes reflect whether a system will be able to continue to function and retain its identity in the face of existential challenges?" We considered attributes for all types of systems, including natural and manmade, physical and institutional, small and large, simple and complex. A number of researchers have defined various attributes of system resilience.

2.1. Previous Efforts to Move from Theory to Application

In his seminal work on the subject, Holling examined the concepts of resilience and stability and described how diversity and connectivity contribute to system resilience [1]. Several years later, in examining the vulnerability of the American energy system, Lovins advanced the concept of managing for resilience by proposing an approach to a design science for resilience, wherein he delineates a set of key attributes for system resilience associated with both engineered and biological systems [22]. These attributes, the descriptions of which focus on a national energy system, included: fine-grained, modular structure; early fault detection; redundancy and substitutability; optional interconnection; diversity; standardization; dispersion; hierarchical embedding; stability; simplicity; limited demands on social stability; accessibility, and reproducibility. With these attributes, Lovins made significant strides in articulating terms of resilience common to both natural and human-designed systems.

Lee examined the essential contribution of adaptive management, the capacity for institutional learning, and the requirements for leadership and collaboration. Adaptive management, in particular, was advanced by Lee, with agencies and organizations implementing adaptive management widely in various forms [23].

Becker and Ostrom examined a series of case studies to formulate general principles for organizing the types of institutions that successfully manage resources in a sustainable manner [24]. They identified eight principles: clearly defined boundaries (for both resources and resource users); proportional equivalence between benefits and costs (rules specifying resource allocation are based on local conditions); collective-choice arrangements (affected participants can influence the rules); monitoring (of resources and user behavior by accountable monitors); graduated sanctions; conflict resolution mechanisms; minimal recognition of rights to organize (outside authorities do not challenge local institutions), and nested enterprises. Becker and Ostrom differentiated the institutional rule sets required for managing renewable *versus* single use resources.

Walker *et al.* examined the relationships between three related attributes of SESs that appear to determine the future trajectory of an SES: resilience, adaptability, and transformability [14]. Regarding resilience, they described four key aspects: latitude—the maximum amount a system can be changed before it breaches a threshold and loses its ability to recover its identity; resistance—the ease or difficulty of changing the system; precariousness—how close the current state of the system is to the threshold; and panarchy—the resilience of the system at one scale is dependent on system dynamics at other scales "above" and "below." Walker *et al.* also discussed the concepts of Stability and Balance in regards to system resilience.

Revisiting that line of research, Folke *et al.* examined how adaptability captures the capacity of a SES to combine experience and knowledge to learn [25]. Folke *et al.* described how "resilience is often associated with diversity" [4]. Discussing the importance of adaptive management (and co-management), they maintained that management actions that build resilience are flexible and open to learning and collaboration.

Folke *et al.* examined ecosystems undergoing change and described the importance of maintaining functional-group diversity and functional-response diversity for the conservation of biodiversity and ecosystems [10].

Walker *et al.* asked "When does it make sense to build resilience and what is the best way to do it for a particular SES?" In answer, they proposed a "resilience analysis and management approach" [11]. They discuss the importance of collaboration among stakeholders in the system to ensure the legitimacy of the effort.

Walker *et al.* advanced a series of concepts about resilience, several of which were proposed as attributes of resilient systems [5]: adaptability (including functional diversity, response diversity, redundancy, social capacity including leadership, social networks, trust, innovation and skills); linkages; institutions for self-determination; capital reserves (natural, social, financial, infrastructure), and learning, memory, and adaptive co-management.

Ostrom's Institutional Analysis and Development (IAD) Framework provided a means for assessing how institutional traits and characteristics and the leadership capacities (and limitations) of key actors at multiple levels within any system can influence system resilience [26]. She discussed the importance of learning capacity in the context of institutional structure. She also cautioned that differences between individual institutions may be so great as to confound simple comparison. This observation may argue for the development of system-specific resilience metrics based on generalized resilience attributes, as is discussed in this article. Ostrom also provided additional explanation of the role of leadership in [27], showing that when some members of a group possess entrepreneurial skills and are respected locally, self-organization to manage resources is more likely. She also addressed the role of norms for reciprocity in building trust that supports collaborative efforts.

Berkes examined the relationship of resilience and vulnerability in regards to natural hazard evaluation [28]. He identified a series of factors relevant to building resilience: learning to live with change and uncertainty; nurturing various types of diversity (ecological, social, political); developing learning capacity; promoting self-organization and autonomy; strengthening local institutions; building cross-scale linkages, and building problem-solving networks. Berkes described the concept of false subsidies, the need for tight coupling of monitoring and response, as well as how adaptive capacity is strengthened by adaptive management and institutional learning.

Examining the relationship between sustainability and resilience, Fiksel described strategies for enhancing ecological resilience including [2]: broaden knowledge sources; increase human ability to cope with change and uncertainty; introduce adaptive management practices; build networks (social and scientific).

In *Resilience Thinking*, Walker and Salt (2006) described a series of key attributes of resilience, including: Functional Diversity, Response Diversity, Modularity, Redundancy, Tightness of Feedbacks, Reserves, and Collaboration [3]. In *Resilience Practice*, Walker and Salt developed a framework for assessing general resilience that is focused on Adaptive Capacity, and specifically the attributes: Diversity, Openness, Reserves, Tightness of Feedbacks, Modularity, Leadership, Social Networks, Trust, and Levels of Capital Assets [6].

Olsson *et al.* examined a series of case studies across the globe, comparing the outcome of various management actions employed as an SES is transformed [29]. They found that leadership and shadow networks are key components for preparing for and effecting such transformations. Leadership functions include: spanning scales of governance; building knowledge; orchestrating networks; communicating understanding and reconceptualizing issues; reconciling problems; recognizing or creating windows of opportunity; promoting and stewarding experimentation as smaller scales; and promoting novelty by combining different networks, experiences, and memories.

Thomas and Kerner described the resilience enhancing potential of adaptive management and collaboration, as well as the negative influence of false subsidies, for energy security policies and programs [30].

Biggs *et al.* examined the current literature to identify seven principles for enhancing resilience of ecosystem services [12]: maintain diversity and redundancy (addressing response diversity, balance, and disparity); manage connectivity (including modularity and nestedness); manage slow variables and feedbacks; foster an understanding of SESs as complex adaptive systems; encourage learning and experimentation (addressing adaptive management); broaden participation, and promote polycentric governance systems (conveying modularity and functional redundancy). The first three of these principles address general SES properties and processes, while the remaining four focus on governance of the SES. The authors state that this is not a definitive set of principles, but one advanced to stimulate further discussion and refinement. They write: "there is a pressing need for a better understanding of how the principles can be operationalized."

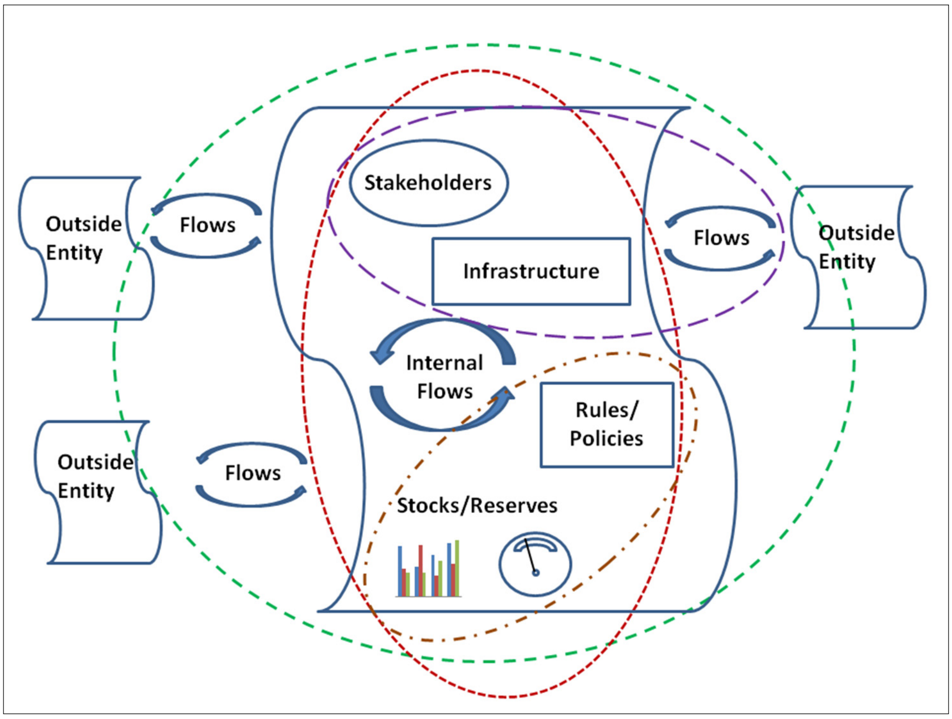
In examining the related concepts and appropriate management context of robustness, resilience, and sustainability, Andries *et al.* discuss how incorporating the principles of managing for robustness can add rigor to managing for resilience [31]. They discuss a number of key attributes for resilient systems: adaptive capacity and response diversity; adaptive management and the capacity to learn; transformability; understanding cross-scale interactions and feedback systems, and collaboration.

Stokols *et al.* discussed how resilience theory relates to social-ecological systems theory [32]. They described the core principles of social ecology and how these contribute to community resilience. They presented a detailed description of the forms of capital available to and necessary for SESs to function. This includes Material Resources: economic/financial capital—financial assets for attaining productivity; natural capital—resources produced through natural processes; human-made environmental capital—physical resources designed and built; and technological capital—machinery, equipment, digital/communications devices. It also includes Human Resources: social capital—relationships among people that facilitate action; human capital—capacities of persons, including skills and information; and moral capital—investment of personal and collective resources toward justice/virtue.

2.2. Stakeholder Analytical Constraints

All resilience analysis methodologies are hampered by a limited knowledge about the system in question and the spatial, temporal, and contextual (environmental, socio-cultural, regulatory, and related) circumstances within which it functions. Figure 1 depicts different levels of knowledge a stakeholder might have about their SES.

Figure 1. Extent of knowledge about SES.



Note: Different system stakeholders have different levels of knowledge concerning the system, its components, and adjacent systems.

Given the complex, adaptive, and stochastic nature of an SES, even a slight difference in system insight could yield a significantly different understanding of the system's dynamics, and therefore resilience, in the face of shocks and perturbations. These limits inherently constrain even the most comprehensive of analyses. As such, an incremental approach to resilience assessment may prove most productive, beginning with examining a system's resilience-specific attributes to develop a baseline understanding of the system's "resilience posture"; this in turn supports deeper investigations of resilience phenomena for which information beyond the normal purview of the stakeholder must be pursued. Moreover, the availability of common analytical terms supports better coordination in the further development of resilience theory.

It should also be noted that the varying degrees of stakeholder knowledge about a system, which may arise for a number of reasons, point to the importance of cooperation in order to work comprehensively within the system.

2.3. The Synthesis of Practical Resilience Attributes

From the above examination of the literature, we can develop an understanding of key traits of resilient systems as conceived by researchers from diverse academic and practicing fields, including ecology, wildlife and fisheries management, water resource management, various branches of engineering, hazard mitigation, risk management, operations research, and institutional analysis.

As stated, our efforts are focused on making theory serviceable to the practitioner, namely the stakeholder seeking to understand and affect the resilience of a system. This requires consideration of certain factors: First, stakeholders usually know their systems best. An outsider may offer new ways of examining a system, but the stakeholder will have both the broadest and the most intimate knowledge about that system. Second, stakeholders have limited time and resources. The perceived value of additional analyses and actions will be weighed against more pressing requirements. And third, stakeholders pay the most attention to that which they believe can most affect their systems. Concern about other possible influences, internal or external, tends to fall off with a decrease in the perceived likelihood and consequence of that influence.

To accommodate these factors, we have sought to develop, derive, and compile resilience analysis terms that: are stated in the language of stakeholders; address easily-assessed system attributes without extensive knowledge of new theory; and promote the ready consideration of the broadest range of factors that could affect system resilience. Prior efforts have tended to yield theory-oriented terms that suit the resilience theoretician; we have sought to provide systems-oriented terms that favor the stakeholder involved in resilience analysis.

In addition to meeting stakeholder needs in their own vocabulary, there is another pragmatic reason for this approach: It is much harder to recognize, understand, and characterize the tremendous variety of systems from the resilience perspective than it is to recognize, understand, and characterize resilience concepts from those systems' perspective. Put another way, the world of possible systems is harder to delineate in resilience-theory terms than resilience theory is to delineate in systems terms.

Expanding on the terms employed by Lovins [22] and addressing open systems (*i.e.*, SESs), and drawing on the authors' own research as well as that of others (as cited above and in the discussion of the individual resilience attributes below), we derived or synthesized from basic resilience theory literature the specific attributes associated with a system's resilience. We identified resilience concepts already expressed in terms stakeholders could easily use to measure or characterize their system, then crafted additional system-oriented terms to capture those concepts not yet described in stakeholder-friendly language, with the focus remaining on what a stakeholder can readily measure or characterize about their system. The resilience literature was revisited to ensure system attributes had been included that would support an assessment of each resilience concept. Finally, several iterations were made to combine like terms under single headings if it could be done without losing pertinent, independent system attributes. The terms are intentionally generic to support a wide variety of systems, with the understanding that stakeholders will employ them in a manner and language aligned with their unique systems.

To meet typical stakeholder needs, we focus on system traits that can be construed from information commonly available within the system, or easily obtained by those stakeholders. The terms form a baseline for resilience analysis, providing a snapshot of the system's resilience posture that could be retaken on a regular basis as part of an adaptive management strategy to maintain and enhance system resilience.

The attributes also form the basis for the first part of an iterative approach to assessing system resilience. Others have sought to capture all aspects of resilience theory in their attempts to postulate metrics, but they require analytical approaches that are not administratively and economically realistic for many system managers. Instead, an understanding of more nuanced aspects of resilience, such as panarchy, latitude, or precariousness, can then be built on the baseline these terms afford.

Finally, stakeholders are the ones who will ultimately decide whether to assess the resilience of their systems, and this hinges on their understanding of the value of these concepts. In many cases, it is best for system stakeholders to apply concepts in order to learn them, as opposed to learning concepts in order to apply them. The availability of user-friendly terms for straightforward system resilience analyses best suits this objective.

Taken together, these attributes are intended to provide the terms that are necessary and sufficient to describe the resilience posture of any system. Care was taken to develop terms that reflect system resilience rather than a desired end-state or system output. While there is significant overlap between the attributes, each term has been found adequately unique to stand as a separate trait. Note that certain attributes will play a more prominent role than others in any given situation, but the entirety of the list is intended to provide a firm foundation for assessing and managing resilience.

The resilience attributes and their definitions are provided in Table 1. They are grouped into categories of Stability, Adaptive Capacity, and Readiness.

Table 1. Resilience Attributes.

Stability Category	
Single Points of Failure	Singular features or aspects of the system, the absence or failure of which will cause the entire system to fail.
Pathways for Controlled Reductions in Function	Whether the functionality of a system, operation, or capability can be reduced in a manner that avoids the overwhelming effects of an unconstrained failure.
Resistance	The insensitivity of the system to stresses of a given size, duration, or character.
Balance	The degree to which a system is not skewed toward one strength at the expense of others.
Dispersion	The degree to which the system is distributed over space and time.
Adaptive Capacity Category	
Response Diversity	The variety and disparity of steps, measures, and functions by which an operation can carry out a task or achieve a mission.
Collaborative Capacity	The capacity to act through coordinated engagement.
Connectivity	How readily resources and information can be exchanged to ensure continued functionality.
Abundance/Reserves	The on-hand resource stores (capital) upon which a system can rely when responding to stress.
Learning Capacity	The ability to acquire, through training, experience, or observation, the knowledge, skills, and capabilities needed to ensure system functionality.

Table 1. *Cont.*

Readiness Category	
Situational Awareness	How well system, component, and functional capabilities are monitored. How readily emerging stresses or failures can be detected.
Simplicity/ Understandability	How well system functions and capabilities can be understood.
Preparedness	The level of preparation in plans, procedures, personnel, and equipment for responding to system perturbations.
False Subsidies	Whether inputs, outputs, or internal processes receive incentives disproportionate or unrelated to their value.
Autonomy	A system manager's authority to select and employ alternate actions, configurations, and components in response to stress.
Enabling Traits	
Leadership and Initiative	The ability to motivate, mobilize, and provide direction in response to disruptions, as well as the ability to assume responsibility and act.

The attributes are sorted into the three categories (Table 2) to provide an easy cognitive basis for organizing the resilience attributes. It should be noted, however, that the attributes do not arise from the categories, but the categories instead arise from a convenient grouping of the attributes. Each of the attributes in fact features some degree of all three categories.

Table 2. Categories of Resilience Attributes.

Single Points of Failure	Response Diversity	Situational Awareness
Controllable Degradation	Collaborative Capacity	Simplicity/Understandability
Resistance	Connectivity	Preparedness
Balance	Abundance/Reserves	False Subsidies
Dispersion	Learning Capacity	Autonomy
Leadership	and	Initiative
Stability	**Adaptive Capacity**	**Readiness**

Notes: **Stability:** The degree to which a system can continue to function if inputs, controls, or conditions are disrupted. It is a reflection of how minor a perturbation is capable of rendering the system inoperable or degraded; the types of perturbation to which the system is especially vulnerable; whether the system can "ignore" certain stresses; and the degree to which the system can be altered by surprise. **Adaptive Capacity:** The ability of a system to reorganize and reconfigure as needed to cope with disturbances without losing functional capacity and system identity. It reflects an array of response options and the ability to learn, collaborate, adapt, and create new strategies to ensure continued functionality. **Readiness:** How quickly a system can respond to changing conditions. It is affected by the physical, organizational, social, psychological, or other barriers, internal or external, that might impede timely response. Readiness is a measure of responsiveness; its converse is entanglement, a measure of the forces impeding responsiveness.

The categories do, however, offer a useful functional construct. Put simply, managers need to know if the system as currently structured and resourced can survive a challenge (Stability), have the ability and options to respond if necessary (Adaptive Capacity), and understand if there are factors that help or hinder that response (Readiness).

2.4. Enabling Traits

Complementing the three categories of resilience attributes, strong leadership and initiative are important factors for achieving resilience. Leadership is necessary to motivate, mobilize, and provide direction in response to disruptions, as is initiative to assume responsibility and act. These enabling traits transcend the categories depicted above and are foundational to the development and maintenance of all resilience attributes.

3. Descriptions and Targeting Queries

The following are descriptions of the resilience attributes, which include capabilities that can be developed and honed to enhance system resilience; capacities that can be accrued or drawn upon to enhance resilience; and conditions that can be recognized and changed to a more resilient system configuration.

Each attribute is presented with associated "targeting queries" (assessed by the authors in [33] (p. 36–46)) to further assist in understanding the intention of each attribute and to support development of metrics for assessing and managing system resilience. (The term "targeting" is used to connote "aiming" for specific parameters within the system that manifest the attributes of resilience (or lack thereof) and can perform as efficient indicators.) The resilience attributes can be used widely and across systems; since effective metrics should be tailored to the specific system being managed, the targeting queries provide a means to bridge the gap and facilitate delineation of well-focused metrics.

Following each attribute description and its targeting queries below, simple examples are offered that depict tangible factors of potential interest in a resilience assessment in the context of two readily understandable systems: a small manufacturing company and a family farm. These systems perform based on dynamic interaction with their environment, but are simple enough to facilitate understanding.

3.1. Stability

Stability refers to the inherent ability of a system, as currently structured and functioning, to remain unaffected or minimally affected by disruptive forces. The concept of stability is well supported by the literature, including the concepts of latitude, resistance, and precariousness described by Walker, *et al.* [14].

3.1.1. Stability Attribute: Single Points of Failure

- Singular features or aspects of the system, the absence or failure of which will cause the entire system to fail (See [22]).

Single Points of Failure can include physical, human, administrative, and other factors. They develop when a system is overly reliant on certain resources or capabilities that, if lost either temporarily or permanently, can threaten functionality. Systems may fail catastrophically, all at once. More commonly, however, specific stresses will challenge singular critical weaknesses in a system. Even seemingly robust systems have single points of failure, although the circumstances inducing emergence may be relatively rare.

Targeting Queries:

- On what physical (components, resources, linkages), human (manpower, skills, leadership, cultural, psychological, political), and administrative (organizational, legal, regulatory) factors does the system depend?
- Are there other critical system dependencies, including simultaneous or sequential functions, external systems, communications, or controls?
- Do single points of failure emerge only after a certain period of time? How well known are the time delays?
- Do single points of failure emerge without warning, or are there forewarnings or other indices? How well known are the warning signs?
- Are all who are affected by the system aware of the single points of failure?

Examples:

The success of the Smith Family Farm (henceforth the Farm) is vulnerable to insect, fungal, or bacterial pests that may damage crops. To diminish this threat, it cultivates several crops that are not likely to fail simultaneously.

Widget Corporation (henceforth Widget), an automotive parts manufacturer, is vulnerable because it requires debt to finance operations, and it can only get operating credit from one bank.

3.1.2. Stability Attribute: Pathways for Controlled Reductions in Function

- Whether the functionality of a system, operation, or capability can be reduced in a manner that avoids the overwhelming effects of an unconstrained failure. (As derived from Lovins' concept of stability [22].)

A system might not be able to retain its full function and identity beyond a certain duration or degree of external stress, but it can "fail gracefully" if it can maintain sufficient functionality long enough to engage compensatory measures or mitigation responses. A function's uncontrollable collapse is mitigated by enhancing Situational Awareness and by developing Response Diversity (specifically redundancy and substitutability) and Preparedness.

Targeting Queries:

- Is there sufficient information available to assess the emergence of system failure modes and to monitor controlled reductions in function?
- Are there methods for controlling a reduction in system function? Can problems be isolated and constrained to limit decline in system functionality?
- Are personnel trained in how to monitor conditions and adjust system components to control system degradation?
- Can a reduction in function be initiated before the onset of an unconstrained failure?
- Can controlled reductions in function be automated? If they already are automated, are they sufficient to handle all possible scenarios? Can manual controls override the automation if necessary?

Examples:

The Farm is able to fallow fields during drought in order to concentrate available water for the remaining crops to ensure a harvest and income.

When an influenza outbreak quickly depletes Widget's workforce, remaining cross-trained personnel are able to operate production lines at a reduced rate to turn out product.

3.1.3. Stability Attribute: Resistance

- The insensitivity of the system to stresses of a given size, duration, or character (See [14,34]).

Different systems, both static and dynamic, possess varying degrees of Resistance to different stressors; some systems are unaffected by stressors that may disrupt other systems. For some stressors, highly dynamic systems may be more resistant, while for other types of stressors, static systems may be more resistant (e.g., a willow tree *versus* an oak, depending on whether they are facing strong, gusty winds or physical assaults to their trunks).

Targeting Queries:

- Does the system have a history of being relatively unaffected by certain types of stresses?
- Can the system endure certain challenges for a known period or with a minimum of additional resources?
- Are there specific conditions under which the system is resistant to challenges and others under which it is more vulnerable or brittle? Can they be determined through analysis?
- Does the system indicate when its inherent resistance will be surpassed and failure will begin?

Examples:

The Farm practices no-till cultivation and plants cover crops, preserving the deep loamy soils from erosion.

Because Widget's process for parts making can accommodate materials of highly varied quality, it is not readily affected by changes in material suppliers and variation in the quality of raw materials.

3.1.4. Stability Attribute: Balance

- The degree to which a system is not skewed toward one strength at the expense of others (See [12,14,34]).

A system is out of Balance when some inputs, controls, processes, or outputs change disproportionately to the rest of the system, thus weakening the system over time or creating vulnerability to certain types of stress. A system retains balance when it does not sacrifice certain strengths in favor of optimizing others. False Subsidies can skew a system out of Balance. Situational Awareness and Preparedness may be able to bring a system into Balance if sufficient Reserves are available.

Targeting Queries:

- Is the system skewed to a particular strength? If so, how is it skewed, and have other system attributes been sacrificed to achieve that strength?
- How well does the system handle a wide variety of missions and challenges?

- Is there a history of system performance faltering when faced with missions or stresses that differ greatly from the norm?
- Is the system subsidized to favor certain features, attributes, or capabilities?
- Can the system be tested to identify imbalances?

Examples:

The Farm has crops that ripen at different times over the course of the year and a timber lot from which to harvest in cold weather, spreading out its workload throughout the year.

Widget maintains complementary output from in-house and out-sourced production lines, has personnel skilled at multiple production tasks, and produces parts for more than one brand of automobile. In addition, when Widget invests capital in new equipment, it also establishes commensurate budgets for maintenance and training for that new equipment.

3.1.5. Stability Attribute: Dispersion

- The degree to which the system is distributed over space and time (See [22]).

Dispersion provides separation from systemic stressors. As a system evolves over time, dispersion may build resilience by fostering independent development of processes and capabilities, disparate strategies for responding to stress, and novel responses to external influences. Dispersion can be employed to reduce Connectivity and ensure that degradation in one part of a system does not disrupt the entire system. It also supports the development of Autonomy.

Targeting Queries:

- How is the system distributed (e.g., distance, time, physical barriers, technical separation, administrative or other organizational division, cultural or social separation, *etc.*)?
- Is separation sufficient to prevent the spread of systemic stresses?
- Are disparate elements free to act autonomously?
- Does the distribution drain resources or slow responses to challenges?

Examples:

The Farm is not physically dispersed, but concentrated in one valley. However the Farm does take advantage of temporal dispersion, as discussed in the previous example regarding the timing of harvests throughout the year.

Widget has two warehouses: a port facility to facilitate shipping and an inland facility sheltered from coastal storms.

3.2. Adaptive Capacity

Adaptive Capacity is the ability of a system to reorganize and reconfigure as needed to cope with disturbances. Adaptive Capacity in ecological systems is "related to genetic diversity, biological diversity, and the heterogeneity of landscape mosaics," whereas, in social systems, it is "the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups" [35].

3.2.1. Adaptive Capacity Attribute: Response Diversity

- The variety and disparity of steps, measures, and functions by which an operation can carry out a task or achieve a mission. (As derived from [1,3–5,22,28,36–38]. See also [12,31,39]. See [13] for discussion of functional diversity.)

Response Diversity refers to the number and variety of options available to achieve a mission or task. It involves all aspects of a system—human-built and organic, subsystems and components, manpower and skill sets, institutional (administrative, managerial, legal, social), formal and casual. The ability to employ alternative components, features, skills, and strategies to accomplish an intended function can enhance a system's ability to withstand stresses. Variety enables system managers to select operational modes and capabilities that are either unaffected by perturbations or able to spread the force of the disturbance over multiple system facets, allowing the system to continue to function as intended. Similarly, response diversity ensures that the system can engage a range of responses to a variety of disturbances. Response Diversity includes such concepts as substitutability and redundancy. (Substitutability is a function of whether substitutable capabilities are flexible enough to work for a range of missions, and whether they can be engaged at different scales of application. It is affected by the amount of effort required to swap out one capability with another, and by whether, and to what extent, any capabilities might be degraded by a substitution. Subsets of substitutability are modularity and standardization, which address how readily system components and features can be exchanged.)

Development of response diversity is needed to counter the typical investments in efficiency and optimization that erode redundancy and flexibility within systems [40].

Targeting Queries:

- How easily can a mission, task, or function be accomplished in different ways or with different resources? How readily can this be done under stressed conditions?
- How many, how varied, and how well known are the options to accomplish a task?
- Are all aspects, components, features, and functions of the system covered?
- To what degree can substitute or redundant capabilities, components, subsystems, controls, resources, skill sets, or features be combined, modified, or directly employed?
- At what cost to the system—immediately or over time—are substitutes employed?
- What burdens are placed on the system to maintain flexibility through redundancies and alternatives? Does the presence of redundancies foster complacency?
- How easily can response flexibility be incorporated into the system? Can changes in rules foster more creative responses to stressors?

Examples:

If the Farm's primary equipment for planting, cultivation, or harvest tasks are inoperable, the Farm employs a variety of back-ups (older equipment and alternate methods) to complete the tasks.

Widget employs the newest production technologies, but also maintains older machines in case the new equipment fails and replacement parts are not readily available. Additionally, while its predominant source of energy is the electric grid, it also maintains a natural gas-powered generator of sufficient size to keep operations going during power outages.

3.2.2. Adaptive Capacity Attribute: Collaborative Capacity

- The capacity to act through coordinated engagement. (As derived from [3,5,12,28,30,32,39]. See also [11].)

Collaborative Capacity refers to the potential of system managers to work cooperatively to ensure system function. It involves engaging linkages—relationships, authorities or permissions, and roles—in a timely and flexible manner to ensure system functionality. It also requires trust and shared understanding of the objectives of the collaboration. Collaborative capacity enables system managers to enlist (or provide) capabilities that would be too burdensome for any single actor to maintain.

Targeting Queries:

- Do personnel know others within the system with whom they can act, and how to make that coordination happen effectively?
- Can linkages be established and utilized in a timely manner?
- Do personnel recognize when to enlist others in collaboration? Is this personality-specific? Can it be instilled through training?
- Are personnel adequately motivated, and do they have the time, resources, and skills needed to collaborate?
- Can it be discerned when the benefits of collaboration outweigh the costs?

Examples:

The family that operates the Farm is close-knit, and they plan and work as a cohesive team.

Widget has good relationships with its material suppliers, who are willing to adjust their supply rates to meet Widget's needs if a surge or sudden drop in production is necessary. Widget's managers and blue-collar workers have a record of working together to solve design and manufacturing problems.

3.2.3. Adaptive Capacity Attribute: Connectivity

- How readily resources and information can be exchanged to ensure continued functionality. (See [11,12,39]. See also [13] for discussion of strong and weak interactions. See [41] for discussion of how inadequate or excessive connectivity may diminish system resilience.)

Connectivity refers to how readily a system can exchange resources and information with its environment and other systems to ensure continued function in the face of existential challenges. It includes cross-scale linkages with systems at larger and smaller scales, *i.e.*, with systems of which it is a part hierarchically and with its own subsystems, as well as any other systems accessible through existing or improvised links. Connectivity confers resilience by the response flexibility and Situational Awareness it enables, allowing systems to proactively alter their readiness posture in anticipation of looming challenges, or to rapidly exploit information and resources in response to surprises. While Connectivity may help avoid system failure by allowing stresses to be spread over several systems, it may also hasten an even larger collapse as the demands of one failing system can overwhelm others from which it draws support. As such, it may be desirable to have connective links that can be decoupled, isolating threatening disturbances and preventing larger failures. Connectivity involves feedback loops that signal how system activities affect connected systems and subsystems; loose feedback loops may reduce resilience by slowing system response to disturbance or masking system affects upon sub- or adjacent systems.

Targeting Queries:

- Where, when, and how are information and/or resources exchanged?
- Are the pathways and links for that exchange known? How well maintained are they? How effective are they? How often are they used?
- Are pathways of connectivity personality-dependent, or can they be accessed and employed by anybody when necessary?
- How does connectivity support response flexibility and situational awareness? How is it enabled by situational awareness?
- What resources are allocated to maintain connectivity?
- Can connectivity pathways and links be severed when necessary to prevent the spread of problems?
- Do bureaucratic requirements slow or prevent action?

Examples:

Due to the independent personality of the farmer, the Farm does not take advantage of opportunities such as the Farmer's Co-operative and University Extension service.

Widget is in constant communication with automobile makers to stay abreast of changes that will affect the design of parts. However, it is receiving—and reacting to—information before those changes have been confirmed, and has had to restrict its communications to the exchange of final, approved new designs.

3.2.4. Adaptive Capacity Attribute: Abundance/Reserves

- The on-hand resource stores (capital) upon which a system can rely when responding to stress. (See [33,39]. See also [3,9,32].)

Abundance/Reserves refers to the surplus within a system of various forms of capital (natural, economic, social, built, *etc.*) that enable it to prolong functionality in the face of a stressor. Abundance provides the resources that support variety, redundancy, preparedness, and other factors contributing to and prolonging a system's resilience.

Targeting Queries:

- What resources does the system maintain for immediate engagement when stressed?
- Are the system's reserves monitored and their limits known?
- Is the system made brittle, vulnerable, or less stable when it employs its resources?
- Are there conditions under which the system's resources are rendered unavailable?
- How is a sufficiency of resources determined?

Examples:

The Farm is vulnerable due to its lack of cash reserves and reliance on credit to finance planting and equipment repair expenditures.

Widget practices just-in-time manufacturing and keeps only a very small supply of excess raw materials. As a result, it must scale back production when faced with delivery problems that constrain availability of materials.

3.2.5. Adaptive Capacity Attribute: Learning Capacity

- The ability to acquire, through training, experience, or observation, the knowledge, skills, and capabilities needed to ensure system functionality. (ibid. See also [1,23,25,26,28,31,39,40,42].)

Learning Capacity involves the ability to draw upon and combine different types of knowledge to support system readiness for, and responses to, disturbances. It may be a trait of individuals as well as organizations. It can be obtained experientially, in a classroom, or through electronic communications, supported by structured and intentional efforts as well as by unplanned and circumstantial events.

Targeting Queries:

- Is there an individual and organizational culture of learning?
- Are there active adaptive management and lessons-learned programs in place?
- Have personnel received expected training?
- Is there institutional support for increased education/training?
- Is the system sufficiently manned to allow personnel the time needed for training?

Examples:

The farmer plans which crops to plant in which locations based on knowledge of what has succeeded on the past and is hesitant to experiment with new approaches. This practice exhibits passive, rather than active adaptive learning.

Widget pays to keep its employees' skills current via on-the-job-training and formal course work. As a result, the company is able to employ new production technologies and practices that enhance Widget's competitiveness.

3.3. Readiness

Readiness is a measure of responsiveness; its converse is entanglement, a measure of the forces impeding responsiveness. While Readiness is affected by physical traits and components, it is more prominently driven by organizational, administrative, legal, social, and related institutional factors. Factors contributing to readiness may arise as a system evolves to a given functional state, and altering those factors may quickly challenge that functionality. Analyses in this realm may reveal unexpected and persistent impediments to a system's operational effectiveness.

3.3.1. Readiness Attribute: Situational Awareness

- How well system, component, and functional capabilities are monitored.
- How readily emerging stresses or failures can be detected. (See [31,36–39].)

Situational Awareness refers to how well the status of a system is monitored. It is a measure of how readily emerging changes and failures can be detected, recognized, and acted upon to minimize adverse effects. Situational awareness includes recognition of a system's potential tipping points and of possible means to avoid passing them; this includes an awareness of how system features and components afford opportunities or vulnerabilities in the face of challenges. It is a measure of the ability to recognize critical dependencies. Situational Awareness relies on the availability and timeliness of accurate and useful information, including sufficiently frequent updates.

Situational awareness is affected by the presence of formal and informal structures (e.g., training and mentoring programs, or regular checks of the system and its environment) that enhance individual and institutional learning. It reflects the ability to recognize critical dependencies and relies on connecting internally among subsystems and externally to other systems.

Targeting Queries:

- Does monitoring take place to detect and identify stresses?
- How timely and understandable is the information provided?
- How comprehensive is the information about the system and its environment? Conversely, how well known are the information gaps?
- Can queries yield additional information?
- How well are personnel trained in knowledge of the overall system; in the use of system monitoring technology; and how to capitalize on advantages designed into the system?

Examples:

The farmer is situationally aware because he is in the fields every day and monitors weather projections and commodity markets on a regular basis.

By monitoring developments in the automotive market and changes in consumer preferences, Widget is able to anticipate new production needs and posture itself to employ the equipment and materials that will satisfy market demands.

3.3.2. Readiness Attribute: Simplicity/Understandability

- How well system functions and capabilities can be understood. (As derived from Lovins' concept of accessibility [22].)

Simplicity/Understandability is the degree to which a function or capability is readily understood by those it affects. This does not mean that a system must be simple to be understood; it refers instead to how well it is comprehended by people acting within the system. It also encompasses an understanding of a system's hierarchical connections, as well as the environment in which it exists and on which it depends.

Simplicity/Understandability can be enhanced through technology (sensors and visual aids that explain system status and function), techniques (procedures that break down the function into easily understood steps), and strategies (the culling of the excess and superfluous). Moreover, familiarity with new items, actions, or rules is gained with daily exposure, while infrequent engagement may foster an unsure grasp that could greatly diminish system function during stressful periods.

Targeting Queries:

- How, and to what degree, is system understanding achieved and maintained?
- Can the complete system be understood by combining partial information from multiple sources?

- How is system understanding shared or transferred? How readily can a newcomer understand the system?
- Can richer information about the system be obtained? How?

Examples:

The Farm's operations are uncomplicated and environmental factors are well understood by the farmer since his family has farmed this location for three generations.

Due to changes in key management, new Widget corporate personnel do not fully understand the company's underlying financial arrangements. Similarly, with the retirement of long-term plant employees and the incorporation of highly automated machines, leadership does not fully comprehend the production line's capabilities and constraints. However, the plants do have adequate records, standing operating procedures, and manuals that can be used to rectify these situations.

3.3.3. Readiness Attribute: Preparedness

- The level of preparation in plans, procedures, personnel, and equipment for responding to system perturbations. (See [34].)

Preparedness refers to the existence of plans and procedures by which a system can respond to perturbations and stressors. It addresses whether contingencies have been considered for expected disturbances as well as disturbances for which little consideration would normally be given but for which the system is particularly vulnerable. Preparedness may involve formal plans that are tested, regularly exercised, and kept current; informal plans that are developed on an impromptu basis; or some combination thereof. Such plans would address how to reinforce or substitute existing subsystems and capabilities, adapt new strategies, and otherwise mitigate lost or threatened functionality.

Targeting Queries:

- Do response plans and procedures exist? Are they formal or informal? Are they flexible? How readily can they be modified for unforeseen circumstances?
- How accessible are plans and procedures? Do those affected know how and where to access them? Are they dependent on specific personnel?
- Are the plans well maintained, frequently updated, and tied to training and exercises?
- How readily implemented are plans and procedures?
- Are personnel well prepared and aware of threats?
- Is equipment well maintained?

Examples:

The farmer does not have written plans for emergencies, but he and his family are well practiced in responding to unexpected conditions and emergencies.

Because Widget has suffered during previous material and manpower shortages, it has developed contingency plans in case those problems reemerge. It has not updated or practiced those procedures, however.

3.3.4. Readiness Attribute: False Subsidies

- Whether inputs, outputs, or internal processes receive incentives disproportionate or unrelated to their value. (See [30] (p. 26), [39].)

False Subsidies refer to whether a system's capabilities or features receive support that exceeds, or is unrelated to, the benefit it provides. These skewing incentives may come in many forms, including financial, material, organizational, legal, social, and cultural. They may be formal or informal, sought or imposed. False Subsidies influence a system to function in a manner different than it normally would, given the natural conditions, the natural range of variability and suite of inputs and outputs, in which the system evolved. The need for subsidies may emerge unintentionally and undetected as a system evolves to perform a given function, hidden in the assumptions underlying the system's formation.

Targeting Queries:

- Are any false subsidies known or readily identified?
- How readily can any subsidies be discontinued, either temporarily or permanently?
- Who controls the false subsidies, and how engaged is that controlling entity in the function or purpose of the system?
- Can false subsidies be converted to assets that do not skew the system?

Examples:

The Farm receives crop insurance and commodity subsidies. These guarantees influence the farmer to plant a higher proportion of high risk – high reward crops than he would if unsubsidized.

The price of certain mined minerals has been kept artificially low due to government subsidies. Widget has structured its entire production capability around materials that are based on those minerals. If national sentiment about the environmental hazards of mineral mining leads government officials to end subsidies, Widget could face drastic increases in the cost of materials and of retrofitting its production line to use new, different feedstock.

3.3.5. Readiness Attribute: Autonomy

- A system manager's authority to select and employ alternate actions, configurations, and components in response to stress. (Per [36–38].)

Autonomy refers to the degree to which an organization, operation, or function can self-select alternate actions, configurations, and strategies to achieve the specific mission or function—essentially, control over its destiny. Autonomy enables an actor to self-organize and choose the timing, order, and priority of actions deemed appropriate for a given circumstance to avoid systemic failure. It allows an actor to select or establish the relationships necessary to function, and to loosen, tighten, or otherwise change the nature of those linkages as necessary. It also allows the actor to make trade-offs that ensure continued system functionality. A system that requires permission in how and when to act may encounter costly delays and receive instructions from those not close enough to fully understand the nature of the problem. Systems defined by Command and Control "pathologies" often struggle to express autonomy [1,4].

Targeting Queries:

- Is the hierarchy of authority or power structure known? Is it necessary, and under what circumstances can it be bypassed?
- Can autonomy be exercised on a situational basis, e.g., in proportion to the stressor, for specific stresses or system features, or on a time-limited basis?
- Are personnel trained to handle autonomous decision-making?
- Does the right or authorization to act autonomously include the ability to negotiate and coordinate with other parties?
- Do parties within and outside of a system recognize others' authority to act autonomously?

Examples:

The Farm operates autonomously within the constraints of federal and state regulations, debt structure, and commodity contracts.

Widget's management approach is highly hierarchical, so employees must receive permission before making even simple changes in how they accomplish their work. When production problems emerge, much time is wasted awaiting authorization to make necessary fixes.

3.4. Enabling Traits

Leadership and initiative connote sentient agency within an SES; complementing the three categories of resilience attributes, they are important factors for achieving resilience in human-managed systems. Strong leadership is necessary to motivate, mobilize, and provide direction in response to disruptions; it is underscored by initiative to assume responsibility and act. These enabling traits transcend the categories depicted above and are foundational to the development and maintenance of all resilience attributes.

Leadership and initiative respond to changing conditions and to the flow of information and resources, and are informed by knowledge of the system's structure, functions, culture, politics, and history. Leaders select from possible responses and create new options in reaction to shocks and disturbances, manifesting as the adaptability and flexibility needed for resilience. Leadership ensures accountability. Leadership tempers initiative, using judgment to determine when to effectively engage a problem and when certain 'normalizing' actions, which are often based on cultural and system design priorities, might create greater system fragility; in such cases, patience and the development of alternate courses of action may be necessary. Finally, leadership and initiative involve knowing how to leverage actions to greatest effect and how to moderate any actions so as to achieve the most desirable outcomes [6,26,27,29].

Targeting Queries:

- Are there actors within the system who fill a leadership role? Are these actors strong leaders?
- Are leaders apparent and agreed upon? Do leaders recognize themselves as such, either on a formal, ad hoc, or implicit basis? Do outside parties, as well as other actors in a system, recognize leaders as well? Do the leaders possess the authority to affect changes and negotiate with governmental agencies and outside actors?
- Do the leaders have enough history within the system to be knowledgeable about system conditions, vulnerabilities, and internal and external threats?

- Do system rules, explicit or implicit, present incentives or obstacles to stakeholder initiative in the face of system challenges?
- Are the leaders comfortable with adaptive management, or do they seek less flexible approaches?
- Do system design parameters and constraints engage and support the performance of leaders when shocks and disturbances challenge initial operating assumptions and change operating conditions?

Examples:

Leadership of the Farm is very clear, with the farmer having authority over all operations. Outside parties recognize the farmer's role as leader of the Farm.

Widget's management approach is reactive and lacks initiative. Employees complain about not having the delegated authority to anticipate needs and adjust processes when needed.

4. Discussion and Conclusions

The resilience attributes were developed to characterize human-managed systems, where policies and practices can greatly alter system dynamics, and they have been refined through a dozen iterations and tested in a resilience assessment that is the subject of a forthcoming journal article. Development of these resilience attributes has been a synthesis of systems engineering terminology and the holistic ecological resilience theory for SESs that has emerged since the 1970s.

Some researchers have developed resilience rating indices based on evaluation variables deemed essential for the continued function of all components making up a system (for example, "does a community have a certified flood plain manager" or "will a certain percentage of road be passable within one week of a major storm"). Cutter *et al.* developed a composite index of disaster resilience indicators for communities. The index is designed to assess current programs and policies for their likely effectiveness in improving disaster resilience [43]. This approach differs from the one described herein in that it does not appear to have been derived from a set of organizing resilience principles, but rather organizes around five sectors of society: social, economic, institutional, infrastructure, and community capital. For each sector, a series of variables have been developed that are presented as universally applicable across systems, but the underlying basis within resilience theory for each variable is not well defined.

A similar approach is taken in the Coastal Community Resilience Index (CCRI), a self-assessment tool to aid community leaders in determining how their community will function following disaster [44]. This tool evaluates critical infrastructure and facilities, transportation, community plans and agreements, mitigation measures, and business plans without examining the underlying principles or resilience attributes of the system being assessed—perhaps appropriate for a lay-person self-assessment, but it may be insufficient for comparison across systems, or for deeper analysis necessary to predict system performance during various categories of disruption. Nor does the CCRI have a process for examining how the individual components within each category may affect the other components within that category or in other categories. Synergies and confounding affects seem to be ignored.

Cumming *et al.* developed an exploratory framework for empirically measuring resilience that focused on four system components necessary to support system identity—their focal points for measuring resilience: structural components that make up the system; functional relationships that link components; innovation variables that relate to development of novel solutions and responses to change; and continuity variables that maintain identity through space and time [41]. The approach presented in this article is similar in that it presents a means for assessing the SES for attributes that can be managed to maintain system identity.

The set of resilience attributes presented in this article reflects a synthesis of many such assessment approaches, indices, and lists developed over several decades, fashioned into a whole for the purpose of providing a comprehensive resource for those professionals tasked with managing systems. These attributes, in concert with the above "targeting queries, enable managers to develop system-specific resilience metrics, which they can incorporate into their plans and programs and make their SESs more robust to disruption. This approach ties measured system parameters directly to those attributes that connote resilience within that system, thus informing managers of how policies and management interventions may relate to building or diminishing system resilience.

As noted earlier, certain variables will take on greater significance than others for a given situation, but taken together the entire collection of attributes is intended to provide a firm basis for beginning the resilience assessment process. Moreover, changes that foster improvements in some areas of resilience may reduce it in others; trade-offs will likely be necessary.

4.1. Limitations

SES stakeholders are usually able to contend with challenges about which they are aware and concerned. The range of resilience attributes provided herein may foster greater awareness of potential concerns not previously considered. However, the attributes, as posited, focus on a steady-state, moment-in-time view of the system. In complex SESs, shocks and disturbances create spatial, temporal, and functional reactions in the system; the extent, trend, or dynamics of these reactions may exceed what the resilience attributes-based snapshot is able to capture. Resilience concepts that address such dynamics include panarchy, with nestedness and cross-scale interactions; thresholds; transformability; latitude and precariousness (within a basin of stability); and acting to manage the slow and fast variables of internal and external threats and dynamics. The resilience attributes also do not consider how management interventions may lead to second- and third-order effects in adaptive and often stochastic, unpredictable systems.

In theoretical terms, it is difficult to characterize the stability domain within which a system resides, including its depth and shape, and the system's location relative to the walls and its ease or difficulty of movement, without knowing the full range of possible stressors and how the system may react to them. Similarly, it is difficult to know where a system resides within the adaptive cycle without knowledge of the nature (type, timing, and strength) of a disturbance as well as the system's status and possible responses to the disturbance. The resilience attributes do not reveal the dynamics driving the system, and require monitoring to discern response trends (directions and magnitudes), shifts indicating the passing of thresholds, and the triggering of novel response dynamics. The predictive value of the resilience attributes for scenario analyses are thus limited by stakeholder understanding of underlying system dynamics, which, as noted, may be constrained by experience, expectations, awareness, and a capacity and willingness to explore.

4.2. Benefits

As noted earlier, all resilience analysis strategies must contend with the challenges associated with assessing and managing the resilience of complex, adaptive systems, and all strategies must, at some point, characterize the systems in question in a consistent manner that supports deeper analysis. This includes modeling, simulation, adaptive management, and similar approaches. Recognizing the limitations mentioned above, there are distinct benefits that may be derived from the resilience attributes. They provide a common approach for characterizing the resilience of different systems that enables program managers and other stakeholders to aggregate resilience assessment results and chart progress toward goals over time and among disparate areas of assessment. (If the underlying metrics for resilience are incompatible, this is difficult to do in any meaningful way.) Additional benefits of a consistent approach include the following:

- Supports informed decision-making by providing a common basis for comparing and understanding resilience across systems.
- Supports identifying and forecasting potential problems and tipping points, instead of learning from failures or from a system on the edge of failure. The whole-system perspective reveals "least-harm solutions."
- Provides additional insights about the effects of policies and practices on system function in the face of unforeseen challenges.
- Provides a solid basis for developing baselines against which to measure trends and progress. This may entail formulating scenarios for qualitatively different future trajectories, then setting resilience metrics-based "waypoints" or "guideposts" in each scenario to provide early warning to managers that the system is evolving in a particular direction. It also supports the evaluation of investment and intervention options [45].
- Provides an additional line of evidence for managing facilities and environmental resources, and for making investment decisions by land use and regulatory agencies, federal installations, states and municipalities, and energy and water utilities, for example.
- Ties to Strategic Planning Objectives and Milestones. Generating quality metrics is typically the most challenging part of the strategic planning process. Using these resilience attributes and targeting queries to develop system-specific metrics can greatly improve strategic plans while incorporating resilience principles.
- Supports Adaptive Management. The resilience attributes lend themselves to assessing system thresholds and sensitivities within an active adaptive management program.

4.3. Applications

The resilience attributes are intended for decision-support at multiple scales within an integrated system. This scalability enables the development of well-aligned organizational resilience strategies, policies, programs, and training. For example, State water managers might focus on building water resilience at several scales: first, by increasing redundant sources of supply for critical applications state-wide (involving the resilience attribute of *Response Diversity*), and then by exercising how to deal with electric power interruptions and water delivery interruptions regionally (*Preparedness* and *Pathways for Controlled Reductions in Function*).

Resilience may be increased immediately; consider, for example, a power utility. By developing additional electric grid interconnections and alert systems (*Connectivity*), managers increase their power networking options. They can also focus efforts to build resilience by conducting drills and exercises to test for *Single Points of Failure,* critical dependences, and the ability to substitute power types for key systems, e.g., testing regular and extended use of multiple fuels within multi-fuel platforms (*Response Diversity*).

Agricultural program managers may reconsider policies with an eye toward realigning or eliminating incentives (e.g., Federal or State tax credits for subsidized water import) that provide funding support but work against making recipients and the regional community more resilient (*False Subsidies*).

Specific areas for potential application of the resilience attributes, and suggestions for how they might be employed, are delineated in Table 3.

Table 3. Examples of Applications for Resilience Attributes and Metrics.

Category	Application
Permanent Federal and State Installations, Park Lands and Reserves	• Perform an assessment of critical infrastructure's resilience to climate change. • Assess forests, range lands, and wetlands for resilience in the face of climate change. • Incorporate resilience metrics into Natural Resource Management Plans, Cultural Resource Management Plans, and similar planning processes. • Perform a facility and infrastructure resilience assessment in response to the 2013 Executive Order on Climate Change Adaption and Resilience.
Temporary Remote Installations	• Use resilience attributes to support "war gaming" and other planning for various ways to configure and allocate resources for military contingency bases or scientific research outposts for enhanced resilience.
Military Operational Energy and Water	• Perform a comparative analysis of resilience in operational energy and water alternatives (e.g., the resilience of energy and water supply and delivery systems as well as of the overall systems using those resources). • Incorporate resilience as an additional line of evidence for making investment decisions.
Watershed Management	• Incorporate resilience metrics into watershed management plans and water quality improvement initiatives.
International Development and Aid Organizations	• Assess the resilience of fragile states (by sector and as a whole) and the resilience implications of various assistance initiatives.
Communities	• Incorporate resilience metrics into community preparedness and emergency response plans. • Assess the disaster preparedness of a community and tailor emergency response exercises toward the weakest sectors. • Evaluate the resilience of rural agro-economies and develop the funding rationale for capacity building and development.
Critical Infrastructure Security and Resilience (Presidential Policy Directive-21)	• Develop uniform analytical metrics and assessment methodology for Federal agencies' response to PPD-21.

We advance the suite of resilience attributes described herein to aid SES managers in recognizing threats and vulnerabilities. The resilience attributes provide a basis for developing resilience metrics that support existing management plans and programs and bring a new perspective for prioritizing objectives, planning resource allocation, and defending investment decisions.

4.4. Future Research

These attributes were tested in a 2013 assessment for the U.S. Army Rapid Equipping Force of the energy and water resilience of a representative combat outpost to a range of difficult shocks and perturbations. The study, which highlighted the resilience vulnerabilities of the combat outpost, provided a preliminary assessment of the applicability and effectiveness of the resilience attributes. While useful, that assessment would be greatly aided by further investigation into the value, strengths, and limitations of the resilience attributes. The following lines of inquiry are suggested:

- Are the terms sufficiently comprehensive and understandable? How easily can stakeholders employ them in creating useful metrics for system management? In addition, can they be used consistently by different users over time?
- How do the attributes relate to and support assessment of such concepts as panarchy, thresholds, transformability, latitude, precariousness, and managing slow and fast external variables? How might they be employed beyond a baseline analysis in an iterative approach to resilience assessment?
- Can the attributes alone characterize system resilience (and if so, to what degree)? Do they surpass simple metrics generated to evaluate infrastructure and emergency and backup functions (e.g., the community resilience index [44])? Are the attributes better suited for framing a deeper resilience analysis (e.g., of thresholds or panarchy)? Are deeper analyses any more reliable than the baseline snapshot offered by these resilience attributes? How can that be tested?
- To what applications do the resilience attributes best lend themselves? This may include vulnerability analyses and gap assessments; assessing the implications of system changes; tracking system conditions and trends over time; prioritizing functions for graceful degradation; and planning investments in infrastructure or other system components.
- How are the attributes best employed? This may include scenario analyses; metrics to guide strategic planning, monitoring programs, and adaptive management; and “Dashboard” depictions for routine monitoring.

In addition to the above research, it may also prove useful to explore the possibility and value of a short, field-expedient version of the resilience attributes. Such a tool would enable stakeholders engaged most closely with a system to contribute to an overall understanding of, and to enhance, the system’s resilience posture.

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Conflicts of Interest

The authors declare no conflict of interest.

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