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# Features of resilience

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**Abstract** The National Academy of Sciences (NAS) definition of resilience is used here to organize common concepts and synthesize a set of key features of resilience that can be used across diverse application domains. The features in common include critical functions (services), thresholds, cross-scale (both space and time) interactions, and memory and adaptive management. We propose a framework for linking these features to the planning, absorbing, recovering, and adapting phases identified in the NAS definition. The proposed delineation of resilience can be important in understanding and communicating resilience concepts.

**Keywords** Resilience · Risk · Policy · Adaptation · Recovery · Climate change · Review

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## 1 Introduction

As our understanding of the world increasingly recognizes the complexity and interconnectedness of social, economic, environmental, and other systems, the concept of resilience has emerged as the touchstone for system managers and decision makers as they attempt to ensure the sustained functioning of key societal systems subject to new kinds of internal and external threats. Ecological, social, psychological, organizational, and engineering perspectives all contribute to resilience as a challenging problem for society. Resilience engineering, for example, has been defined as “the ability of systems to anticipate and adapt to the potential for surprise and failure” and has been associated with a shift in safety paradigm acknowledging that system coping is important when prevention is impossible (Hollnagel et al. 2006). Ecological resilience, on the other hand, refers to the ability of the system to absorb and withstand shocks, with an emphasis on persistence (Holling 1996). Resilience is used as a metaphor to describe how systems react to stressors, and to bridge the gap in understandings between fields, resilience needs to be discussed less abstractly, separating the metaphor from the science. Across the many diverse lines of inquiry, there are weak linkages between concepts and methods for resilience. Useful ideas and results accumulate and partially overlap, but it is often difficult to find the common areas. Plus the different technical languages hamper communication of ideas about resilience across the different contributing disciplines and application problems.

In this paper, we identify features of resilience that are common across applications of resilience. The National Academy of Sciences (National Research Council 2012) defines resilience as “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." The common features include critical functions (services), thresholds, cross-scale (both space and time) interactions, and memory and adaptive management. These features are related to the National Academy of Sciences definition of resilience (Table 1), including the temporal phases of the NAS definition to emphasizing the importance of time in all conceptualizations of resilience. We acknowledge that partitioning time into phases can be considered an oversimplification of temporal relationships; however, the NAS phases serve as a framework for organizing the described set of common features of resilience. This paper takes an exploratory approach to understanding resilience by describing how these common features relate to different applications of resilience.

The concept of *critical functionality* is important to understanding and planning for resilience to some shock or disturbance. *Thresholds* play a role in whether a system is able to absorb a shock and whether recovery time or alternative stable states are most salient. *Recovery time* is essential in assessing system resilience after a disturbance where a threshold is not exceeded. Finally, the concepts of *memory* describe the degree of self-organization in the system, and *adaptive management* provides an approach to managing and learning about a system's resilience opportunities and limits, in a safe-to-fail manner. The paper is organized such that each feature of resilience is discussed in more detail and then summarized in Table 1.

## 2 Critical functions (services)

Understanding the resilience of systems focuses on assessing how a system responds with respect to sustained functioning or performance of critical services while under stress from an adverse event. In assessing resilience, then, it is necessary to define the critical functions of the system. Stakeholders play a key role in defining critical functions; operationalizing resilience concepts depends on identifying the resilience of what, to what, and for whom. In addition, system resilience depends on how the boundaries of the system are drawn (i.e., the chosen scale of interest) and the temporal span of interest. Scale is often dictated by the social organizations responsible for managing the system based on temporal and spatial dimensions (Cumming et al. 2006). Thus, stakeholders influence how resilience is assessed in terms of defining both critical functions and

**Table 1** Resilience features common to socio-ecology, psychology, organizations, and engineering and infrastructure, which are related to the temporal phases from the National Academy of Sciences definition of resilience

| NAS phase of resilience | Resilience feature | Description by application domain | | | |
|---|---|---|---|---|---|
| | | Socio-ecological | Psychological | Organizational | Engineering and infrastructure |
| Plan | Critical functions (services) | A system function identified by stakeholders as an important dimension by which to assess system performance | | | |
| | | Ecosystem services provided to society | Human psychological well-being | Goods and services provided to society | Services provided by physical and technical engineered systems |
| Absorb | Thresholds | Intrinsic tolerance to stress or changes in conditions where exceeding a threshold perpetuates a regime shift | | | |
| | | Used to identify natural breaks in scale | Based on sense of community and personal attributes | Linked to organizational adaptive capacity and to brittleness when close to threshold | Based on sensitivity of system functioning to changes in input variables |
| Recover | Time (and scale) | Duration of degraded system performance | | | |
| | | Emphasis on dynamics over time | Emphasis on time of disruption (i.e., developmental stage: childhood vs adulthood) | Emphasis on time until recovery | Emphasis on time until recovery |
| Adapt | Memory/adaptive management | Change in management approach or other responses in anticipation of or enabled by learning from previous disruptions, events, or experiences | | | |
| | | Ecological memory guides how ecosystem reorganizes after a disruption, which is maintained if the system has high modularity | Human and social memory can enhance (through learning) or diminish (e.g., post-traumatic stress) psychological resilience | Corporate memory of challenges posed to the organization and management that enable modification and building of responsiveness to events | Re-designing of engineering systems designs based on past and potential future stressors |

system scale. For example, the Resilience Alliance workbooks for practitioners assessing resilience in socio-ecological systems ask stakeholder groups to envision the system and scale of interest, possible disturbances, and to identify vulnerabilities (Resilience Alliance 2010). Further, with respect to psychological resilience, individuals are responsible for assessing resilience through self-reported inventories of protective factors (e.g., adaptable personality, supportive environment, fewer stressors, and compensating experiences) (Baruth and Caroll 2002). It is common practice to use questionnaire responses of stakeholders to assess resilience in psychological and organizational systems. Therefore, the definition of critical functions or services in psychological or organizational domains may be more subjective than perhaps in environmental or engineering systems. Regardless, stakeholder-informed identification of critical functions is a necessary, preliminary step to understanding and discussing system resilience.

## 3 Thresholds

The concept of resilience involves the idea of stable states or regimes in which a system exists prior to a disruptive event. Systems are able to absorb changes in conditions to a certain extent. However, if a shock perpetuates changes in conditions that exceed some intrinsic threshold, the system moves into a different regime where the structure or function of the system is fundamentally different. It is the balance of positive and negative feedbacks that can cause a system trajectory to exceed a threshold and degrade system performance (leading to the "collapse" phase of the adaptive cycle) (Fath et al. 2015). While a simple example of a threshold is the tipping point of a canoe, Kinzig et al. (2006) discuss cascading thresholds related to the ratio of grassland to woodland with respect to a farming-based society and economy. The nested nature of systems contributes to the possibility of cascading effects when a threshold at one scale is crossed and causes disruptions at other scales (Kinzig et al. 2006). The sensitivity of system and sub-system performance to changes in inputs can be used to determine resilience thresholds. Resilience thresholds within organizations are linked to the adaptive capacity of the organization and of the management scheme utilized. Identifying thresholds prior to exceeding them is difficult and an area of intense research (Angeler and Allen 2016). When a threshold is crossed, return is difficult, especially where hysteresis is present. Where or when a threshold is not exceeded, resilience is still relevant, but measures of return time are more appropriate. These concepts are interlinked, and return time may slow as the resilience limits of a system are approached [i.e., critical slowing (Dakos et al. 2008)].

## 4 Time (and scale)

Resilience is often considered with respect to the duration of time from a disruptive event until recovery (or until the system has stabilized in an alternate regime), and the spatial extent of the system of interest. We consider space and timescales as inextricably linked; changes in critical functionalities are highly correlated in time and space, but frequently one aspect of scale is considered without covarying the other; this is a deeply flawed approach. There is frequently an emphasis on minimizing time to recovery where full or critical levels of services or functions are regained. *Engineering resilience*, in particular, has a focus on the speed of return to equilibrium, but this measure of resilience does not adequately consider the possibility of multiple stable states (Walker et al. 2004), nor account for non-stationarity. However, return to equilibrium provides important information about the resilience of a system to perturbations that don't cause the system to exceed a threshold and enter into an alternative regime. The timing of a disturbance, and how it corresponds to the state of the system, can also impact the observed effects in system performance and functioning. Particularly in the psychological domain, it is important to consider the timing of disruptive events within an individual's lifetime. For example, children might be more susceptible than adults to negative psychological impacts from an event, though this is not always the case. Further, resilience requires an appreciation for system dynamics over space and time. For example, it is often thought that resilience is linked to the dynamics of certain key variables, some of which are considered "slow" changing and constitute the underlying structure of the system while others are "fast" changing representing present-day dynamics (Fath et al. 2015). Furthermore, interdependent systems often display mosaics of functionality, services, and redundant capacities in space and time. Panarchy theory captures this cross-scale structure in complex systems (Allen et al. 2014). The theory emphasizes the need for a system (or system-of-systems) approach that appreciates interactions across time and space to understand system dynamics and resilience, especially as they relate to the adaptive cycle.

## 5 Memory

Memory of previous disruptions and the subsequent system response to a shock can facilitate adaptation and make systems more resilient. For example, Allen et al. (2016) observe that ecological memory aids in reorganization after a disruptive event. Memory tends to be maintained if the system has high modularity or diversity (Fath et al. 2015).

While the concept of memory may not be applicable to all systems, depending on how the system boundaries are drawn, it is particularly prevalent in human systems. It has been noted that socio-ecological resilience is enhanced by a diversity of memories related to the knowledge, experience, and practice of how to manage a local ecosystem (Barthel et al. 2010). Institutional memory can extend beyond that of individuals. For example, institutional memory is responsible for maintaining lessons learned from previous challenges to the organization or to similar organizations (Crichton et al. 2009). Memory of an event in the short term often results in increased safety or resilience through anticipation of a shock or disruptive event through enhanced resistance or adaptive capacity, though in the long term the memory of the event fades (Woods 2003). In each case system-wide sensing or monitoring is essential to capture changes in salient driving conditions and critical functions; whereas, subsequent sensory data analysis or feedbacks assist with the development of memories and important causal relationships. Understanding system behavior, even under "normal" conditions, over time can be important for predicting reaction to stressors.

In human physiology, responding to repeated stressors produces long-run changes in the physiological systems affected by the series of events that evoke stress responses. Generally, the shocks endured in the past serve as good predictors about how the system (human or not) will respond to uncertain, future shocks. While memory of a past experience can have a negative impact on an individual, in some cases, memory can enable positive adaptation whereby these individuals are better able to cope with future stressors. However, social memories tend to influence individuals' interpretations of reality, and thus, maladaptive social memories can decrease individual and societal resilience (Barthel et al. 2010).

## 6 Adaptive management

Under changing conditions, however, memory of past disturbances and responses may not be sufficient for maintaining system performance or critical functionality. The objective should not be to create a system that can sustain against one type of stress, as is common when designing for robustness. Instead, temporal and spatial flexibility is important for the absorbing or adapting to different shocks and stresses (Woods 2006). Flexibility allows the system to navigate through the adaptive cycle while maintaining functionality (Fath et al. 2015).

The concept of adaptive management acknowledges uncertainty in knowledge about the system, whereby no single management policy can be selected with certainty in the impact (Linkov et al. 2006). Instead, alternative management policies should be considered and dynamically tracked as new information and conditions arise over time. Accordingly, management is able to adapt to emergent conditions, reduce uncertainty, and enhance learning in a safe-to-fail manner. By adjusting response strategies in advance to disruptive events, management is able to build a readiness to respond to future challenges. Anticipation and foresight lead organizations to invest in capabilities to deal with future disruptions and prepare for multi-jurisdictional coordination and synchronization of efforts such that the system adapts prior to disturbances. Thus, system-wide sensing (monitoring), anticipating disruptions, adapting, and learning (from both success and failure) occur proactively and in a perpetual cycle (Park et al. 2013), or until key uncertainties are reduced.

## 7 Conclusions

There are a number of common features of resilience linked to the planning, absorbing, recovering, and adapting phases identified in the NAS definition. This paper has discussed these common features in the context of different application areas and related to the NAS temporal phases of resilience. In summary, preparing or planning for resilience involves stakeholder identification of critical functions of the system and the strategic monitoring of those functions. Intrinsic thresholds or boundaries determine the amount of disturbance a system can absorb before the system enters an alternate regime, whereby the structure and/or critical functions of the system are different. Whether the system transitions to a new regime or remains the same, the time until the system (performance and critical functionality) recovers from a disturbance is used to assess resilience. Finally, memory and adaptive management facilitate system coping to changing conditions and stressors, even in an anticipatory sense. These features, along with stakeholders and scale, are important across domains in understanding and communicating resilience concepts.

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