Resilience and Robustness in Ecological Systems

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Introduction

The notions of resilience and robustness in ecological systems generally refer to the ability of the system to continue to maintain its essential character in the face of disturbances, endogenous or exogenous. In different traditions, the words "resilience" and "robustness" are alternatively used to describe this property. In some usages, however, the term *resilience* is reserved for the ability of a system to recover from displacement, and the more general term *robustness* used to combine resistance to displacement with the ability to recover (see Levin & Lubchenco, 2008); in other usages, as adopted for example by the Stockholm Resilience Centre, the term *resilience* refers to the combination of both (Holling, 1973).

The notions of resilience and robustness in any system are tied to whatever macroscopic descriptors are defined to be of interest. For an organism like us, the concept is clear - it's what keeps us healthy; and a physician has unambiguous descriptors that define the health of the organism. For an ecosystem, the concept is more difficult, because an ecosystem is not a well-defined evolutionary unit; rather, it is in general operationally defined in terms of the species that coexist in some area or region, together with the abiotic environment within which they coexist, including especially the nutrients whose dynamics sustain those species. The definition of resilience or robustness for such a system is not unique, but depends upon the level of description. Species may come and go without affecting the overall persistence of the features that make the system recognizable; and, in fact, the dynamic nature of species turnover, for example during ecological succession, may be essential to the maintenance of the more macroscopic features of the system.

The question remains as to what macroscopic features should be the focus of resilience and robustness strategies for ecosystems. Are particular species essential to maintain in their own right, or should the focus be on broader functional groups that sustain critical ecosystem processes? (Kareiva & Levin, 2003). This is a key question, not easily answered, because which properties are valued depend on one's perspective. For some, the intrinsic nature of individual species is paramount; while for others, the value of particular features of biodiversity are to be evaluated through the filter of the services humans derive from ecosystems. The more general notion of *ecosystem services* in theory combines services that can easily be given economic value with those,

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like the intrinsic nature of species, that cannot unequivocally be assigned such values (Daily et al., 2000). However, in practice, because of the difficulties in quantifying non-market values, the ethical and aesthetic dimensions receive short shrift.

Any manager of an ecosystem, whether a natural one or an engineered one (such as in agriculture), must first determine the goals of management - namely, what is to be preserved. There is basically no unequivocal way to do this for natural systems, and hence the management objectives in general cannot be separated from the socio-economic context.

Risk and resilience

A fundamental issue in assessing the robustness of any system is that of *systemic risk*, namely the potential for localized disturbances to spread contagiously and become global problems (May, Levin, & Sugihara, 2008; Frank et al., 2014). Ecological systems differ from many other systems, like banking systems, in that they are essentially self-organized (Levin, 2005; Helbing, Yu, & Rauhut, 2011). When assessing the properties of resilience for engineered systems, one may rely on the fact that design principles have guided the construction of those systems. Similarly, for individual organisms, natural selection has shaped the regulatory processes and other characteristics to maintain the resilience of critical functions. For ecosystems, however, no such feedback mechanism has shaped their properties. There is, of course, another sort of process, a selection process that biases what we observe in favor of systems whose properties allow them to persist longer (Lewontin, 1977; Levin, 1999; Lenton & Lovelock, 2000), but this is different than a design principle.

Over time, organisms have evolved to balance exploration and exploitation in ways that approximately optimize their fitnesses in a game-theoretic sense; successful organizations must do the same. To the extent that resilience or robustness means the maintenance of the status quo, it must be balanced against exploration, which carries risk. Whether systems are designed, evolved, or self-organized, the most resilient and robust systems will find this balance, or else they will not be able to persist in changing environments. Problems arise, of course, when the conditions that gave rise to that balance are disturbed, as for example through climate change. Carlson and Doyle (2002) describe a wide class of resilient systems that are "robust, yet fragile"; that is, they may be robust to a class of perturbations for which they have been selected, yet fragile in the face of novel ones. For example, comparing the resilience or robustness of tropical and temperate ecosystems only makes sense with regard to appropriate classes of disturbances; tropical ecosystems may be more robust with respect to normal stresses, but more fragile in the face of novel ones.

Design principles can be applied to managed ecosystems, like forests, fisheries and agricultural systems, in order to balance success in current environments versus adaptive capacity to deal with novel ones (Clark, Jones, & Holling, 1979). Redundancy and diversity provide insurance and allow for innovation, while modular construction can limit systemic risk (Levin, 1999; Simon, 2002; Simon, 1962). More generally, managers have much to learn from how evolution has shaped robustness, for example through the evolution of the vertebrate immune system (Levin & Lo, 2015). Evolution has shaped the properties of the immune system to deal with the fact that, predictably, unpredictable pathogenic threats will attack us all. The immune system is hierarchical in the sense that the first line of defense involves barriers to invasion, things like skin. When those barriers are breached, the threat must be recognized as such, generalized responses (like macrophages) invoked, while adaptive responses (specific antibodies) evolve and provide memory. Such a hierarchy is very suggestive for the development of protection for a wide class of systems.

Risk appetite and tolerance

One of the most basic concepts in fisheries management is that of maximum sustained yield, and related concepts like maximum sustained rent (profit) similarity emphasize constancy of system properties. Constancy is obviously an attractive feature in many respects, since it implies sustainability and predictability. However, focusing entirely on robustness in this sense erodes the capacity for learning and exploration, and may lock systems into domains of performance that are suboptimal. In changing environments, the lack of innovation may in fact doom the system to collapse.

More generally, robustness may not be a desirable feature, for example if a system is stuck in an unproductive configuration like a hypoxic or eutrophic lake. Economic recessions and depressions provide familiar examples (Levin et al., 1998). Indeed, principles of sound investment carry over little changed to ecological management. Risk tolerance and discounting dictate the degree to which bet-hedging and insurance arrangements need to be applied to maintain long-term performance, sacrificing short-term gains for long-term persistence.

In any context, from investment strategies to the management of businesses and natural systems, and indeed to our own lives, one has to balance a tolerance for risk against the potential for the greater rewards that risk can bring. Any management situation that involves collective agreements necessarily involves trading off the ways different individuals discount the future. For example, politicians and CEOs typically would have steeper discount rates (because they need to show results) than stockholders and the general public; people who are worried about where their next meal is coming from have steeper discount rates than those who can afford to plan for retirement. In general, there is great heterogeneity within any population between risk-takers and more conservative planners, and indeed even individuals in making decisions balance these tendencies. This leads inexorably to non-constant discounting (for example, *hyperbolic discounting*), and all the complexities it introduces (Weitzman, 2001; Dasgupta & Maskin, 2005; Laibson, 1997).

Societies aggregate individual preferences, just as individuals do for their internal conflicts, and solutions typically average tolerances through compromise decisions and insurance arrangements. The science and politics of how to do that effectively still needs a great deal of work, as evidenced by the lack of agreement within our own societies on such fundamental existential issues as climate change.

Transition, adaptation, transformation

Transitions and transformations can affect systems in unplanned ways or can be designed to transform systems from less desirable states to better ones. In the former case, it obviously would be desirable to have early warning indicators, as well as built-in feedback loops that minimize the damage. Certain classes of transformations show characteristic patterns of change, and efforts to identify them in biological and other systems have been a focus of research for at least a half-century (Guckenheimer, 1978). More recent efforts (Scheffer et al., 2009) have borrowed heavily from the literature on phase transitions in physics. Like the earlier efforts, these are promising directions, but care must be taken not to expect uniform patterns.

Management of any system must anticipate transitions, and plan for transformations that are as painless as possible, while resisting the temptation to stick too long with losing strategies. Such issues are at the center of current research in business strategies (Reeves, Levin, & Ueda, 2016;

Reeves, Levin, Harnoss & Ueda, 2018). Obviously, such issues are front and center for environmental systems and societies as well.

In the face of global change in climate and other features, overall robustness must embrace change, and the challenge becomes how we engender change without severe disruptions. There are numerous examples in the environmental literature - for example, the recognition after years of alternative practice that small controlled fires remove tinder and increase the robustness of forests to major catastrophes, or the use of diversification in agriculture to minimize the potential for pathogen outbreaks or other system-wide disturbances. In financial systems, small corrections are generally regarded as healthy for the long-run viability of markets. Such principles must apply as well to our social and ecological systems, embracing adaptability, if our societies are to survive.

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The relevance of the papers cited below is explained in the text, but especially recommended are the seminal papers by Herbert Simon and C. S. Holling, which lay the foundation for robustness and resilience, and Levin's Fragile Dominion, which develops such notions for ecological resilience.

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