Title: Trade-offs among resilience, robustness, and performance and how we might study them

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Summary/Abstract:

Biological systems are likely to be constrained by trade-offs among robustness, resilience, and performance. A better understanding of the shape of trade-offs is important for basic biology, as well as application where biological systems can be designed for different goals. We focus on redundancy and plasticity as mechanisms governing some types of trade-offs, but mention others as well. Whether trade-offs are due to resource constraints or 'design' constraints (i.e. structure of nodes and link s within a network) will also affect types of trade-offs that are important. Identifying common themes across scales of biological organization will require that researchers use similar approaches to quantifying robustness, resilience, and performance, using units that can be compared across systems.

Introduction

The concepts of robustness, resilience, and performance transcend biology. Indeed, biologists have borrowed the terms from engineering and physics. Today they are applied to topics as disparate as corporate governance, macroeconomic trends, and interpersonal relationships. In any system with constraints, resources allocated to one goal will not be immediately available to meet other goals. Sometimes it is possible to achieve multiple goals simultaneously, but when that is not possible or when goals inherently conflict, then trade-offs must exist. For a range of reasons, robustness, resilience, and performance are typically desirable goals for biological systems at scales from molecular networks to ecosystems. Empirical evidence across these scales suggests that very often there exist trade-offs between performance on the one hand and robustness and resilience on the other. Identifying and understanding the causes and mechanisms underlying these trade-offs is essential to developing predictive and generalizable models of how systems respond to perturbations and how, when necessary, one might attempt either to maximize performance, robustness, or resilience or to minimize the trade-offs. These models will improve our understanding of the unifying principles of Biology and can be applied to such issues as food security (plant response to environmental change), infectious disease control (virulence vs. transmission), and ecosystem services (water retention and flood control). **This paper aims to develop a framework for evaluating these goals and trade-offs and to suggest empirical and computational approaches for such evaluations**.

Why do we care

We live in an era of novel perturbations and changing perturbation regimes. We need to 1) understand how high system performance can be maintained and 2) learn to design robust and resilient biological systems that also function at high performance levels. As noted above, a key challenge is that strategies that increase resilience or robustness often entail trade-offs that reduce performance, or trade-off robustness against resilience. In addition to fundamental questions in basic biology, there are important applications that come from all scales of

biological organization. For example, gene networks that are robust and resilient and that can maintain high performance despite perturbations can enhance disease treatment efficacy. A robust and resilient agricultural system will maintain food and biomass production in the face of climate perturbations, while a robust and resilient biomass digester will maintain fuel production despite heterogeneous feedstock supplies. It will be critical to identify actions that can increase robustness and resilience while minimizing performance losses, or, at a minimum, to identify the shape(s) of trade-offs curves so informed decisions about optimal degrees of robustness and resilience are possible.

Background
Trade-offs
Trade-offs are a universal concept across many fields of inquiry. Using a particular resource for one kind of outcome prevents that resource from being used for something else. In behavioral biology, time used for predator detection or avoidance cannot be used for foraging or mating. Energy allocated to growth cannot be allocated to reproduction. These resources can be measured in units of time, space, energy, or other resources (e.g., grams of nitrogen or phosphorous). In molecular biology, the number of ribosomes serves as one limit to transcription, in conjunction with the time cost of transcription.

While trade-offs are universal, the currencies that impose limits can change over time, space, levels of biological organization and biological study system. The nature of the resource currency may also alter strategies biological entities take to avoid or respond to perturbations. Similarly, discount rates for performance costs can differ among systems, favoring either performance or robustness and resilience, depending on the balance of risks and future rewards (Lerdau 1992). Thus, the loss of species with high or low discount rates may have different cascading impacts on communities or species interactions. Factors that affect resource allocation patterns in the face of trade-offs may include baseline conditions, the ability to sense or predict perturbations, and evolutionary constraints on mechanisms.

Because both perturbations and the responses to them have an explicit temporal component (duration of the perturbation, and length of recovery time), comparing studies at different scales of organization will require a way to standardize durations. For example, metabolic pathways may respond to short-term ("pulse") perturbations at a scale of minutes to hours, whereas plant communities may respond to pulse perturbations at scales of months to years. Identifying characteristic time scales that could be used for standardizing rates across scales is a challenge for reintegrating biology.

In addition, other trade-offs can occur at more abstract levels, in parallel with the idea of "design" trade-offs as opposed to "resource" trade-offs. One example of a trade-off between metrics of response to perturbation in ecological networks is the inherent trade-off between local stability and robustness (to co-extinctions) of mutualistic networks, i.e. networks of partner species interacting for mutual benefit. Local stability is defined by the eigenvalues of a system, and in particular if the real parts of all of the eigenvalues in a dynamical system are negative. In the early 1970's, Robert May (1973, *Nature*) showed that as systems become more complex, in terms of having both more nodes and more linkages between nodes (i.e. "edges" or "links"), their probability of local stability is reduced. By contrast, in mutualistic systems where species are interacting for mutual benefit, having more potential mutualistic partners, and more

connections, increases robustness to coextinctions. Thus, there is a strict trade-off between local stability and robustness to coextinction (in mutualistic systems), driven by the patterns of node and link distributions in network structure, rather than by any limiting resource.

Robustness and Resilience
We are using a broad definition of robustness and resilience as *responses that limit the effect of a perturbation on a system*. There are many different facets of how systems respond to perturbations, and different terms are used in different fields, including different subfields of biology. For example, in ecological networks, "**robustness**" typically refers to "robustness to coextinction" or the number of secondary species extinctions resulting from a single-species removal. This is equivalent to "**attack tolerance**" in physics and network science more broadly, i.e. the response to the knock-out of a single node in a network. This idea has broad application in biology, e.g. the removal of a single neuron from a neuronal network, or a single gene from a genetic network, even if robustness is not defined in this specific way for researchers in neuroscience or genetic networks. And robustness has other definitions in other fields, for example the general idea of relative system immobility in the face of perturbations or disturbances, or the ability of system to maintain function despite being moved to a new state.

Similarly, in the broad field of dynamical systems "**resilience**" has a crisp definition, the return time to an equilibrium following a perturbation, as measured by the eigenvalues of a dynamical system (represented by a Jacobian matrix, evaluated at an equilibrium). Again, in other contexts "resilience" is taken to be a more general idea of a system's capability of being able to rebound from a disturbance. Throughout this paper we will mostly refer to "robustness and resilience" again in terms of their general and broad definitions of properties that reduce the effects of perturbations on a system, and we use both terms to indicate that there are multiple facets that should be considered.

We acknowledge that robustness and resilience, for any system or scale, cannot be defined in isolation; robustness and resilience are measured in response to a particular type and scale of perturbation (i.e. robustness must be defined with reference to a domain of perturbations), and a system that is highly robust or resilient to one type of perturbation may not be against a different type of perturbation. For this reason it will also be important to develop ways to predict future perturbation regimes, including changes to multiple external factors.
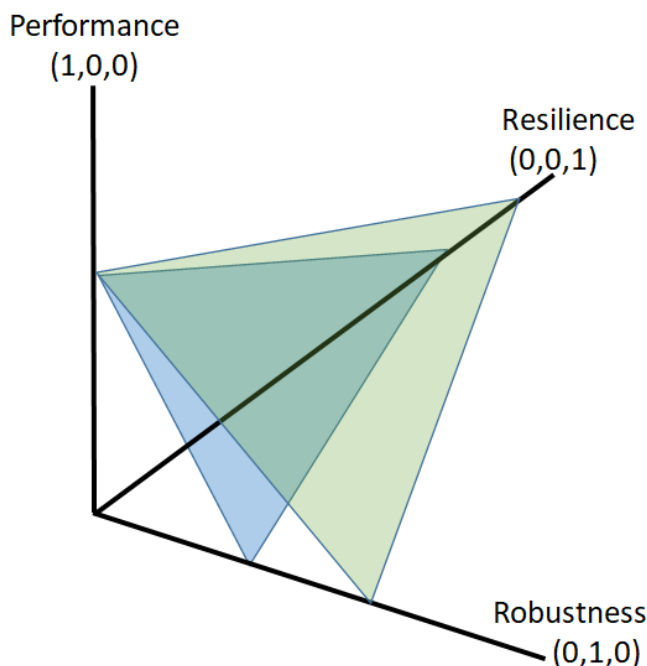
Performance
The act of performing, the *doing* that results from life itself, is exceedingly difficult to define, conjuring Supreme Court Justice Potter Stewart's remarks on determining a legal definition of obscenity: "I know it when I see it" (Gerwirtz, 1996). At different scales of organization, 'performance' means very different things, but it often refers to the rate of a process or the amount of a product. At cellular scales performance is often considered in terms of anabolic or catabolic rates. At organismal scales, a common metric is the number of offspring ("fitness" in the Darwinian sense). In communities and ecosystems, processes such as carbon fixation/mineralization, nitrogen mineralization, and energy flux are common metrics of performance. The critical feature that all of these performances share is that their units can be expressed as rates, either individuals, grams, or moles produced or consumed per unit time. In order to compare system performance in meaningful ways across scales and types of study

systems, we must develop ways to compare performance metrics. Using rates to evaluate performance has the advantage that rates are typically measurements on a "ratio scale" (c.f. Measurement Theory)—i.e. measurements based on a true zero.

Related to the concept of performance is that of efficiency. Whereas performance is an amount produced or consumed by the entity in question over a specified time interval, efficiency is the ratio of one performance to another. For example, at the subcellular level the quantum efficiency of photosynthesis is the ratio of photons absorbed to carbon dioxide molecules fixed. At the organismal scale, growth efficiency is the ratio of biomass accumulated to biomass ingested. At the ecosystem scale, water-use efficiency is the amount of carbon gained for the amount of water lost. Although the two concepts of performance and efficiency are intimately connected, they differ both the way described above and in another important manner. There are strong reasons from first principles to think there may be inherent trade-offs between performance and robustness and resilience, but efficiencies may vary positively with robustness and resilience.

- Figure 1 represents hypothetical combinations of performance, resilience, and robustness, with planes connecting the values along the three axes. In this example, the system represented by the blue plane has relatively high resilience but moderate levels of performance and robustness. Due to resource constraints, any shift towards higher robustness may be offset by lower levels of resilience. However, if a system is able to acquire (or is supplied with) higher levels of the limiting resource, represented by the green plane, the entire surface could move further from the origin and it would be possible to gain higher levels of both robustness and resilience simultaneously. Despite this potential route towards having higher levels of both robustness and resilience, a trade-off still exists at any given level of resources.

Potential Barriers

Contexts

The context within which perturbations affect systems, be they organelles, cells, organisms, or ecosystems, can have dramatic effects on performance, on robustness and resilience, and on the relationship among these three. Whether a system's response to a perturbation is generic or specific under varying contexts can ultimately produce different outcomes of trade-offs. Further, how the contexts of perturbations are sensed and information about contexts is transferred still remains a challenge to identify in many systems. Sometimes the contextual effect involves the availability of complementary resources. For example, a two-week drought may have very different impacts depending on whether or not groundwater is accessible, or on the precipitation history of the site. Western pines are far more robust to bark beetle attacks when they have adequate water than when they have been suffering a water deficit. Although the principle that systems with lowered performance because of one perturbation tend to have lower robustness and resilience with respect to others is empirically well supported, a concerted effort to study system responses to multiple perturbations under varying contexts is needed.

Performance metrics

It is important to bear in mind that performance can be measured with quite different units, depending on the process under consideration. While this diversity of metrics for performance can create problems for efforts to compare performances across different processes, it is orthogonal to the question of the relationships among performance and robustness and resilience. The key for studies of these relationships is to use similar units across performance, robustness and resilience. For example, if a plant's photosynthetic performance is measured as grams C fixed per unit mass of plant per unit time, then resilience of photosynthesis will be the time constant for photosynthesis to return to its pre-perturbation rate. That is, the units used for any one analysis of robustness or resilience must correspond to the units employed in the performance measure.

Scale

From a broader perspective, generalizing patterns of trade-offs in robustness, resilience, and performance across scales of biological organization will be essential to developing unifying principles of biology. In some cases, trade-offs at one scale are shown to affect performance at another, thus quantification and significance of robustness and resilience depend on which scale they were measured. For example, the transfer of energy in trophic systems can be altered by the magnitude of stress-induced changes in herbivore physiology and resource choice, which has downstream effects on nutrient assimilation efficiency, nutrient content of soils, and plant-species composition, and energy transfer up the food chain. In this case, the performance at the ecosystem level (i.e., productivity) is affected by the robustness of the response to a stressor experienced at the organismal level that results in a trade-off between survival and reduced efficiency and greater energy demands. The issue of scale in understanding these trade-offs also arises when we consider performance in multi-dimensional parameter space, but this hurdle is diminishing with improved simulations of experimental perturbations on complex traits (e.g., pattern formation in embryonic development).

Similarly, comparisons of trade-offs when measuring robustness, resilience, and performance will depend on temporal scale, both in the duration of perturbations and the system's response. Since resilience is a function of time, comparing across systems will require a standardized measure related to the temporal scale on which the process occurs. Further, studies will need to have an unbiased determination of *when* in time the previous state a system must return to in order to be considered resilient.

Mechanisms
Mechanisms: Redundancy
Redundancy is a mechanism by which systems can generate robustness or resilience under some conditions. For example, experiments have examined yeast with single transcription factor knockouts, for the full complement of all known transcription factors in the yeast genome. Interestingly, only ~3% of the binding target genes of those transcription factor removals had any impact in terms of their level of transcription. Thus, the transcription factor network in yeast is highly robust to single gene knockouts. Furthermore, that robustness seems to largely be driven by redundancy: nearly all of the binding target genes each interact with multiple transcription factors, which allows for essentially uninterrupted function in the face of a perturbation (single gene knockout). Similarly, in the aforementioned mutualistic network example, having more positive interaction partners allows for systems to be more robust to the loss of a single interaction partner.

Because we are focused on trade-offs, it is important to note that redundancy can have costs. As mentioned previously, increasing the complexity of a dynamical system decreases its probability of local stability, strictly defined. In addition, redundancy can also hypothetically reduce performance in some cases. Redundancy can carry costs in terms of the resource use required to have a functional "back up". For example, a bacterial cell with many redundant copies of the same or similar genes is likely to reproduce at a slower rate than a competitor with fewer redundant copies, given the time and resource cost of DNA replication. Another cost can come about if the multiple redundant actors that contribute to functioning (transcription factors, neurons, species, etc.) vary in their functional efficiency. If one bird species is by far the most efficacious at dispersing the seeds of a particular plant, by having a redundant assemblage of bird species, that plant may suffer reduced seed dispersal. Indeed, biodiversity-ecosystem functioning theory (with substantial support from experiments) suggests that the highest-performing communities are those with the greatest *complementarity* between their functional aspects, i.e. when the species functional roles complement one another. Restated, this is when there is the *least* amount of redundancy among species roles.

Thus, there may be an inherent or general trade-off between performance (functioning) and redundancy. This would be an interesting area for future explorations. For example, if there is a bacterial species with sufficient variation in the number of transcription factors among genotypes, it would be interesting to see if functioning trades off with robustness to single transcription factor losses. This would of course require variation in both transcription factor number and identity to ensure that the identity of the transcription factors does not confound the results.

Mechanisms: Plasticity

We define plasticity as the capability of system components to change in response to some exogenous factor. For example, organismal phenotypic plasticity is some developmental, physiological, morphological, or behavioral change in response to an environmental cue. If we consider biological systems as networks, comprised of nodes and links, plasticity can manifest itself both as changes in the nodes themselves (for example, organismal phenotypic plasticity) and also in the links. For link changes, these can be driven by, for example, behavioral plastic changes in nodes (predators changing prey preference, to change linkage patterns).

We posit that plasticity should generally lead to greater system resilience and robustness, and it may—in some cases—do so in ways that reduce apparent trade-offs with system performance. For example, plasticity can allow for resource allocation changes that maintain performance. This kind of mechanism also operates at organismal and even smaller scales, e.g., in biochemical or genetic pathways that allow for alternative substrates or binding targets. At an organismal scale, there is evidence that plants exhibiting greater phenotypic plasticity can respond to environmental perturbations such as droughts more successfully, in terms of survival and reproduction.

There is evidence that plasticity can lead to enhanced network response to perturbation. For example, in organismal consumer-resource networks (food webs and/or mutualistic networks), plasticity in foraging (i.e. adaptive foraging or optimal foraging) can lead to changes in both the intensity of feeding and the identity of which resources are foraged on. This plasticity, in turn, has been shown in models to improve system performance in response to perturbation, such as increased persistence of nodes (species) in these networks. While this work has been framed in community ecological terms, the models used to explore these concepts should be general to many consumer-resource systems at multiple levels.

While these examples indicate a potentially strong mechanistic role for plasticity in driving resilience and robustness at various levels of biological organization, more work is needed to elucidate general patterns of exactly how and why plasticity plays this role. Similarly, this kind of mechanistic understanding would increase our ability to understand when plasticity might enhance vs. detract from robustness. One potential way in which plasticity could detract from robustness is if it carries substantial costs. In organismal-level studies of plants, however, several studies have attempted to characterize the costs of plasticity and these costs have not been conclusively demonstrated to date, despite some excellent studies designed for this purpose.

Future directions
Understanding the mechanisms underlying trade-offs between robustness, resilience, and performance is a necessary first step towards developing coherent approaches to maximizing one outcome, e.g., performance or robustness, or minimizing the magnitude of the trade-offs themselves. Even more critical will be the identification of common currencies and measurement units to facilitate communication and comparisons across fields; without common metrics it will be difficult to identify generalities that span levels of organization. A consistent use of 'rates of production of X, dX/dt' as performance metrics is a starting point, because proportional changes in performance can be compared across systems. The scaling of appropriate time units for measuring resilience, however, as a function of return *times* to an

initial state, is an outstanding challenge. The standard eco-evolutionary trick of re-expressing times in units of generations may have broad application, for example scaling down to the timing of cell division or the transcription time of a single focal gene. Still, such scaling does not always work, and may not be applicable to metabolic pathways or interaction networks.

Finally, there is exciting potential in the identification and classification of mechanisms that confer robustness and resilience to different types of perturbations. It will require creativity and interdisciplinary communication to recognize whether mechanisms in different systems or at different scales are analogous or homologous. The development of future theoretical frameworks that integrate across scales will likely require knowledge of underlying mechanisms in order to provide useful predictions about responses to potential perturbations beyond the range of current data. Further, to address global anthropogenic change, it becomes essential to predict responses of systems to future perturbations. This cross-scale approach to studying trade-offs is an essential first step in the reintegration of Biology.

Citations:

Lerdau, M. (1992). "Future discounts and resource allocation in plants." Functional Ecology **6**: 371-375.

Gewirtz, P. (1996) On I Know It When I See It, 105 Yale L.J. 1023 (1996).

May, R. M. (1973). Stability and Complexity in Model Ecosystems. Princeton, Princeton University Press.