COMMENTARY

Managing variance: Key policy challenges for the Anthropocene

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Developing effective governance structures for the fair and sustainable use of benefits that flow from shared natural resources is arguably one of the defining challenges of our time. Addressing this challenge has been extremely difficult because the associated governance problem is multifaceted and multilayered. Governance structures must address at least three interrelated issues: (*i*) equitable distribution within and across generations of affordances for well-being; (*ii*) social dilemmas associated with providing shared infrastructure and preventing overexploitation of shared resources; and (*iii*) coping with deep uncertainty and variability that complicates decision-making and planning efforts. Addressing these issues will often require us, both as individuals and in groups, to act against our natural tendencies. Familiar examples related to the first two issues include delaying rewards for the sake of future outcomes and overcoming our aversion to the "sucker's pay-off" to build sufficient trust to address social dilemmas. Recent work suggests that this is also true when coping with uncertainty and variability in benefit flows while sustaining them over the long term. Specifically, Carpenter et al. (1) develop an important set of ideas related to managing environmental variability that may cause two of our natural aversions to collide. The authors suggest that we must learn to live with a certain amount of variability if we want to enlarge the safe operating space for exploited ecosystems. Just as with delayed rewards, humans are averse to variability in benefit flows related to subsistence (2, 3). More challenging yet, because allowing variability in ecosystems may well involve reduced exploitation, we may be required to forego present consumption as well as tolerate variability to maintain a safe operating space for humanity.

Of these challenges, coping with uncertainty and variation in benefit flows is the most difficult to conceptualize. Although all three are difficult to address in practice, delayed consumption and developing trust and institutions for collective action are at least conceptually tractable. Most people easily grasp the notion of consuming less today to leave more opportunities for future generations. Similarly, most of us know that the effectiveness of formal regulation of behavior is limited; at some point groups must self-organize and work together based on trust. Even the rather subtle notion of a social dilemma can be effectively communicated with simple examples, such as a shared pasture (4). In stark contrast, conceptualizing decisions involving variability and uncertainty is very difficult and intuition can often mislead us (5). Carpenter et al. (1) bring fresh insights to this difficult problem by analyzing subtle trade-offs associated with managing variance on short time scales and resilience on longer time scales.

To appreciate the significance of Carpenter et al.'s analysis, it is useful to place it in a typology of "robustness-fragility" trade-offs (Fig. 1). Of course, there are numerous approaches to cope with variation but three classes are particularly relevant to human–environment interactions: (*i*) direct (designed) modifications to the resource system (e.g., ecosystem) structure to deliver desired benefit flows (Fig. 1*A*); (*ii*) combination of multiple resource systems with variable but negatively correlated benefit flows to deliver desired benefit flows (Fig. 1*B*); and (*iii*) introduction of feedback responses to variations in the resource system state to stabilize benefit flows (Fig. 1*C*).

The most common, oldest, and iconic example of deliberate system modification is irrigation infrastructure aimed at reducing high frequency (e.g., monthly and annual) temporal variation of water availability for farming. Irrigation systems are examples of hard human-made infrastructure that fundamentally alter how a resource system (e.g., a watershed and landscape) transforms an input signal (annual precipitation) into an output signal (spatiotemporal distribution of water on the landscape). Just as Carpenter et al. (1) suggest, agriculturalists want the flow of water, an ecosystem benefit, to be predictable and exhibit low variance from month to month during the growing season and from year to year across growing seasons. This suppression of short-term variance brings with it a number of long-term fragilities. The most obvious is the susceptibility of irrigation infrastructure to damage from large, low-frequency (one per 50 or 100 y) flood events that can interrupt water flows for extended periods and impact food supplies for large populations with devastating results.

The most familiar example of the second approach comes from modern financial market institutions that allow agents to easily hold and exchange multiple financial assets to reduce variance in their rate of return. There are also many examples of the use of trade networks to "hold" multiple physical assets to reduce variance of food supply (6). Again, this comes with potential fragilities that emerge when asset portfolio adjustments by individuals interact through the network and lead to decreased stability and increased variance at the exchange-system level (7).

The third, and perhaps most powerful, approach to reducing variance is through the introduction of regulatory feedback loops. Regulatory feedback is very simple conceptually: if a benefit stream varies too far from a preset point (or strays too close to the boundary of a safe operating space) feedback temporarily changes flows in the resource system (as distinct from changing its structure) to drive it back toward the present target. The most familiar example is the reduction in the variance in elevation of an airplane when turbulence is encountered. In fact, it has been argued that layers of feedback regulation driven by a need to maintain robustness (decrease variance) in uncertain environments may be a fundamental feature of persistent, complex, biological patterns (8) [i.e., the ecosystems that Carpenter et al. (1) study]. Regulatory feedback networks—although conceptually simple and extremely powerful—are dangerous (9). Here, fragility enters as an integral feature of the coupled resource system–controller dynamics and is manifest as the system recovers after a

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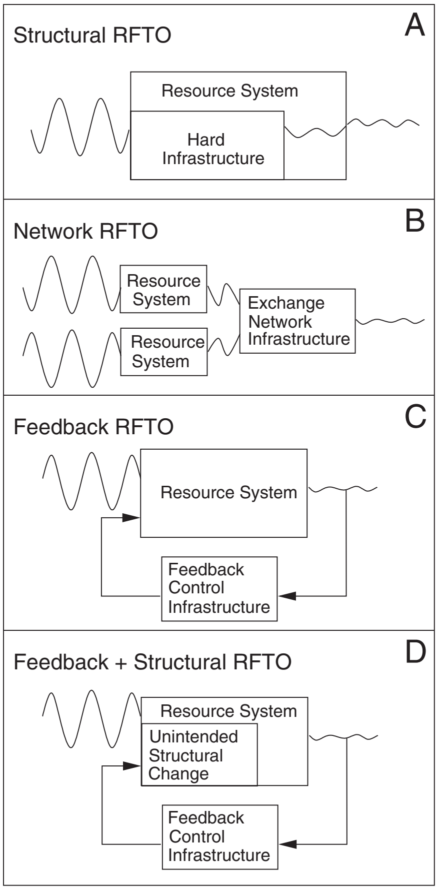

Fig. 1. Resource systems are driven by variable input signals (*Left*). System modifications can reduce the variance of the system outputs, such as benefit flows, (*Right*). (*A*) Built infrastructure (e.g., canals), directly impacts resource-system structure to reduce benefit flow variance. RFTO: built infrastructure is not isolated from variable input signals and thus is exposed to very costly failures because of low-frequency, high-amplitude events (e.g., 100-y floods). (*B*) Exchange infrastructure enables multiple resource system outputs to be combined and smoothed. Infrastructure can be isolated from resource system inputs. RFTO: variance in distribution of benefit flows in the exchange network can be amplified by network dynamics. (*C*) Feedback infrastructure influences the internal dynamics of the resource system to reduce output variance. Infrastructure can be isolated from resource-system inputs. RFTO: Increased dynamic complexity generates potential for amplification of rare events. (*D*) Combination of *A* and *C* addressed by Carpenter et al. (1).

shock. In this case, high-frequency robustness (reduced variance) must be paid for in low-frequency robustness (8, 10).

These different approaches to reducing variance highlight three types of robustness–fragility trade-offs (RFTOs): (*i*) the structural RFTO, (*ii*) the network RFTO, and (*iii*) the regulatory feedback RFTO. The Structural RFTO (Fig. 1*A*) is perhaps the easiest to identify: the inherent trade-offs associated with building a dam or dike are clear. The Network RFTO (Fig. 1*B*) is likely more difficult to identify because individual actors can't see how their actions cascade through the network. Observers of the network can, however, restrict some actions across the network and reduce some of these fragilities. The regulatory feedback RFTO (Fig. 1*C*), however, is the most problematic because the fragilities are hidden by the very power of feedback networks to fine-tune systems to appear robust (i.e., exhibit low variance), and are revealed only as a result of rare failures (9).

The RFTO typology helps highlight the full extent of the difficulties raised by the analysis in Carpenter et al. (1). Consider that in most cases humans interact with the natural environment in systems with partially designed components (e.g., the built environment, institutional arrangements) and partly self-organizing components (e.g., ecosystems, climate). In this situation, implementation of a regulatory feedback (e.g., a policy to control phosphorous loading, fishing harvest, or grass biomass to reduce variance) may cause the underlying structure of the self-organizing component being controlled to change. Now the situation is one involving both regulatory feedback and structural RFTOs (Fig. 1*D*).

Carpenter et al. (1) explore the interaction between these two types of RFTOs using three well-developed nonlinear ecological models for the self-organizing subcomponent of the human–environment system: phosphorous loading in lakes, renewable resource harvesting, and grazing in a semiarid savannah. Although there are studies regarding the processes by which various management regimes impact the structure, and hence resilience, of these systems (11, 12), this is the first that explicitly treats the interaction between management regimes focused on variance suppression and shifting system structure. Carpenter et al. (1) very neatly show that using feedback to reduce variance may not only generate feedback RFTOs but may also induce unintended structural shifts within the resource system that reduce its intrinsic self-organizing capacity to cope with shocks; that is, shrink the resource system's safe operating space. The authors show this is true for all three cases, supporting the generality of this phenomenon.

This work highlights several policy challenges that will become more pressing in the Anthropocene. First, as climate change increases variance in local ecosystem drivers, there will likely be stronger incentives for managers to implement ever more variance-reducing feedbacks that, in turn, will exacerbate feedback RFTOs. Second, as a growing number of previously relatively isolated resource systems become linked into a global network, network RFTOs [i.e., teleconnected vulnerabilities (13)] will become more probable. Third, Carpenter et al.'s (1) call to tolerate variance in benefit flows at the ecosystem level poses challenges at the individual level. As we progress toward a planet of 9 billion people, we may reach a threshold beyond which we will no longer be able to use exchange networks to reduce variance at the system level while allowing it at the individual resource-system level. There may simply not be a sufficient number of resource systems with requisite negatively correlated benefit streams.

This brings the discussion back to the first two sustainability challenges I opened with: How will we fairly distribute the burden associated with the "variance tolerance" required to enlarge the safe operating space at the planetary scale? How will we prevent free riding on the efforts of those who live with variance by those who do not? These questions are suggestive of how challenging governance in the Anthropocene could become. Carpenter et al. (1) succinctly articulate multiple trade-offs between managing short-term variance and maintaining a safe operating space that we will likely have to navigate in the context of conflicts over fairness and collective action problems. This emerging knowledge regarding fundamental limits on our capacity to cope with variability and change across temporal scales should spur us to action long before those limits are approached.

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