PERSPECTIVE

Governing complexity: Integrating science, governance, and law to manage accelerating change in the globalized commons

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The speed and uncertainty of environmental change in the Anthropocene challenge the capacity of coevolving social–ecological–technological systems (SETs) to adapt or transform to these changes. Formal government and legal structures further constrain the adaptive capacity of our SETs. However, new, self-organized forms of adaptive governance are emerging at multiple scales in natural resource-based SETs. Adaptive governance involves the private and public sectors as well as formal and informal institutions, self-organized to fill governance gaps in the traditional roles of states. While new governance forms are emerging, they are not yet doing so rapidly enough to match the pace of environmental change. Further-more, they do not yet possess the legitimacy or capacity needed to address disparities between the winners and losers from change. These emergent forms of adaptive governance appear to be particularly effective in managing complexity. We explore governance and SETs as coevolving complex systems, fo-cusing on legal systems to understand the potential pathways and obstacles to equitable adaptation. We explore how governments may facilitate the emergence of adaptive governance and promote legitimacy in both the process of governance despite the involvement of nonstate actors, and its adherence to dem-ocratic values of equity and justice. To manage the contextual nature of the results of change in complex systems, we propose the establishment of long-term study initiatives for the coproduction of knowledge, to accelerate learning and synergize interactions between science and governance and to foster public science and epistemic communities dedicated to navigating transitions to more just, sustainable, and resilient futures.

governance | complex systems | social–ecological–technological systems | law and science

The Great Acceleration as a Science and Governance Challenge

Global environmental change reflected in the "Anthro-pocene" epoch coincides with unprecedented rates of change in social and technological systems brought about by climate change, biodiversity loss, globalization, the digital revolution, development, and population growth (1). Increasing interdependence within social, ecological, and technological systems (SETs) presents obstacles to both adaptation and transformation as the results of change unfold. In particular, it introduces a high level of uncertainty into how these systems will respond. Rising to this challenge requires a new focus for government and new approaches at the interface

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between science and governance. To understand this, it is useful to begin with an example of the types of problems that led modern environmental and natural resources law to a predominant mix of regulatory and market-based approaches, with regulation implemented by science-based agencies in which a layer of political bureaucracy generally stands between the scientist and the decision maker.

Garrett Hardin's (2) 1968 example of the inevitable tragedy of degradation of a common pool resource (e.g., public grazing land, air, water) where benefits of use are individual and harm is spread across all users, led him to suggest that either regulation or private ownership were necessary to align the interests of resource users with the public good. Hardin's underlying focus was on population growth, but as with many who cite his article, it is the attention he called to the logical consequences of increasing per capita resource exploitation on environmental health that is of relevance here. In a time of slow change in human interaction with the environment, the simplicity of Hardin's commons made plausible a binary choice between science-based regulation and private property markets. Furthermore, in a simplistic view of the commons, science and governance could be understood as independent. Elected and appointed officials set goals. Scientists and engineers designed the means to optimize for those goals (3, 4).

Imagine Hardin's pasture today with the recognition of a much more interdependent system of nature, infrastructure, and society facing accelerating change (Fig. 1):

Development encroaches on the floodplain, moving grazing into the uplands where it depends on irrigation. Technology led to the development of dams for irrigation, flood control, and carbon-free hydropower for the area, but those same dams block salmon migration and reduce sediment flow. Salmon are critical to regional indigenous culture. Aging water infrastructure in poor neighborhoods presents water quality threats to health. Coal mining in the headwaters has resulted in destruction of habitat and downstream heavy metal contamination, but is the sole job source for much of the rural area. Alternatives for a viable rural economy do not currently exist. Agricultural intensification and encroachment on wildlands lead to transmission of disease from wild to domestic animals, raising concerns over the possibility of zoonosis. External factors include changing global markets for agricultural products and coal, pandemic, and climate change. The latter is driving lower snowpack in the headwaters of the river, longer periods of drought, higher decadal floods, and species migration into new geographic regions. The wildland–urban interface has potential for catastrophic wildfire. Efforts to move toward carbon neutrality will increase the value of the hydropower system and threaten rural livelihoods dependent on coal.

Aspects of this generalized example play out in many SETs throughout the world. There is broad consensus that due to the accelerating rate of change and uncertainty in its trajectory and outcome, we cannot design our way to top-down, transferrable, science-based solutions in complex SETs commons (3–5).

The scholarly community led by Nobel Laureate Elinor Ostrom has shown that in complex settings Hardin's tragedies are being avoided as mixtures of public and private actors self-organize to solve social–ecological problems. This empirical work documents that self-organization leading to emergent "adaptive governance" allows the consideration of values, local knowledge, and different world views. Adaptive governance provides an avenue for tailoring responses to the emergent properties of complex systems and is widely viewed as capable of handling complexity, uncertainty, and change (5–7).

"Governance" in this context involves any form of collective action taken to manage the common affairs of society and occurs as intentional and self-organized interactions among governments, private groups, and formal and informal institutions (6, 8, 9). The use of the term has increased as private actors, public–private partnerships, and collaborative processes play an increasing role in collective action, addressing a wide range of social challenges (8, 10–12). Within this larger crucible, governance produced through self-organization of nonstate actors is increasing in response to the real and perceived failures of government (6, 8, 10), the global reach of economic actors and other nongovernmental organizations (NGOs) (12), and to increasing complexity (8, 10, 11). We
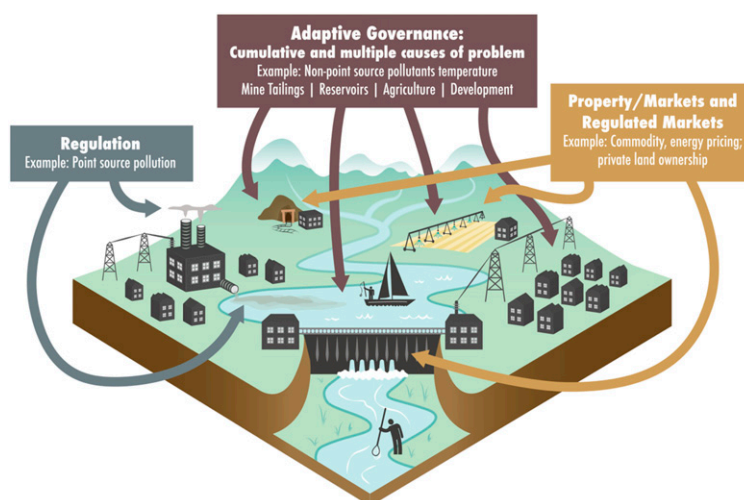

Fig. 1. This stylized drawing of a modern watershed illustrates the dynamics of a complex commons and the need for a multipronged governance response. Discrete pollution discharges, such as those from the factory and sewage treatment plant, are sometimes appropriate targets for simple regulation. However, given the multiple, distributed human actions with cumulative or synergistic impacts; the complex interactions between human activity and environmental change; the competing interests of watershed users; cross-jurisdictional effects; and external drivers of change, the limited focus of regulatory regimes regulation alone is often not sufficient to manage all interconnected problems afflicting heavily used modern commons. Illustration credit: Megan Caye Ashe (Washington State University, Pullman, WA).

focus further on the governance of "SETs," defined as interacting natural and human systems in which the technological component represents the increasingly complex realm of interaction between the human and natural systems (13), reflecting the type of subsystems members of our team focus on. The technological component includes the infrastructure and products that humans develop from and in the natural environment (14), and the "methods, processes, materials, machines, tools and techniques" used for that development (13).

Our own work and that of others have documented the emergence of self-organized adaptive governance in complex SETs settings across the globe [e.g., North America and Australia (11, 15, 16), Europe (17–19), and Africa (20)]. Unfortunately, change through emergent governance is not keeping pace with the rate of environmental and social change, frequently runs into legal barriers, and does not always focus on the public good. Of critical importance, prevailing approaches to funded research produce a snapshot in time that is inadequate to inform governance in rapidly evolving SETs. It is therefore useful to explore 1) whether theories such as complexity and ecological resilience theory that help us understand change in ecological systems might also inform how government can speed up and steer emergent adaptive governance systems; 2) whether government might also have a role in steering emergent adaptive governance toward the public good and in providing restraints and checks on processes that lack attention to legitimacy (defined in this context to include transparency, accountability, and access to decision making, as well as democratic processes of deliberation and voting), equity, and justice; 3) whether a focus on steering adaptive governance toward effective evolution changes the role of science in informing governance of SETs including presenting a need for the adaptation of efforts to gather, synthesize, interpret, and communicate scientific information through time; and finally, 4) whether the science needed to inform the governance of changing complex SETs requires a different type of scientist trained within a governance setting.

In a decade-long project that brought together ecologists, human geographers, and experts in institutional analysis, with legal scholars, we found that complexity science, despite its limitations in application to society, provided a bridging theory and common language that fostered communication across disciplines. This common frame allowed us to explore means for government to accelerate new approaches to governance of SETs (11, 21). Complexity science, with its roots in mathematics, and resilience with its roots in ecology, do not fully account for social attributes such as agency, power, and empathy. Social scientists are beginning to embrace complexity and to grapple with these unique human attributes in that context (22, 23). However, the integration of these diverse approaches with complexity is only beginning to emerge at the level needed to inform governance of SETs. Importantly, the application of complexity science to governance cannot address questions of governance equity—i.e., governance for whom? The involvement of nonstate actors means that emergent governance may, at best, only address problems for certain segments of society, and at worst, may choose goals that are detrimental to society. We address this gap by integrating the work of political scientists and legal scholars—disciplines that acknowledge the role of agency, power, and empathy including the potential negative impact a self-organized societal response to change can have on legitimacy, equity, and justice. We then ask what a broader role for government in facilitating emergent adaptive governance means for scientific research and education at the science–policy interface. We conclude that response to modern rapid drivers of change (such as

climate change) requires research that allows for deep analysis of complex SETs through time and understanding of governance, law, and science as integrated knowledge systems. This in turn requires education of a new type of "public" scientist. This article presents the culmination of that project.

Interdisciplinary Methods for Bridging Science and Governance

Boundary spanning research must begin by identifying common ground and developing a common language (24). We begin by exploring what governance scholars can learn from complexity science about emergent behavior, including adaptation and nonlinear change in SETs, and thus, how the language of complexity science might provide a bridge between those who study SETs and those who study governance. Through a focus on system resilience, complexity science has changed the way science understands systems as varied as ecological systems (22, 23) and the growth and development of cities (25). While many agree that social systems, including legal and governance systems, are complex adaptive systems (26, 27), the application of complexity theory to social systems is contested due to the theory's failure to account for human attributes related to consciousness and free will (28). It is well understood that governance is strongly influenced by these attributes, particularly human agency, power, and empathy (9, 29).

While we recognize these limitations of complexity science, we nevertheless find the concepts of system complexity and resilience useful in understanding the coevolution of legal and governance systems with other systems embedded in complex SETs. Our focus is not on whether complexity theory can describe or predict patterns in social behavior, but on whether it can inform efforts to adjust legal systems to accelerate governance responses to system change.

Six attributes of complex systems are relevant to this exercise of informing governance:

1) Self-organization. The interaction of components of complex systems leads to relatively stable states independent of any intentional design (4, 30–32). For example, markets composed of numerous individual decisions self-organize due to interaction of supply and demand and lead to stability in economic systems over multiple geographic scales (33, 34). As documented by Ostrom and her laboratory (6, 7, 10, 35), social systems also self-organize both within formal systems of government and in their absence to sustain the resource systems on which they rely.

2) Emergence. Emergence is a key attribute of complex systems and applies to the novel properties resulting from self-organization that would not be predicted from study of system components alone (32). An important facet of the use of complexity science to inform governance is that emergence is contextual, dependent on system history and surroundings. As a result, understanding regarding the capacity of a particular system for adaptation or transformation may not be transferrable, even among seemingly similar systems (31, 34). In governance systems observed to self-organize in response to a problem, the possibility of innovation exists (36). A challenge for government in managing systems undergoing change is to support the innovation and adaptation associated with bottom-up emergence of governance while maintaining overall social and economic stability (21, 33, 37).

3) Networks. Networks in governance systems allow response at the scale of a problem despite lack of "fit" with formal institutions (21, 38, 39). They also mediate public–private interaction.

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The capacity for government to work across jurisdictional and sectoral boundaries is critical in times of rapid change due to the inability to predict the scale and scope of problems that will emerge (21).

4) Feedbacks. Feedback within a system can accelerate change but can also be useful in learning. Negative feedbacks buffer system changes and lead to system stability. Positive feedbacks accelerate change and may destabilize systems. In social systems, positive feedback may be a factor in the current increasing wealth gap in many western democracies, with accumulation of wealth leading to greater agency and power among the wealthy, thus increasing wealth, and poverty leading to decreasing agency and power and thus deeper poverty (9). The concept of feedbacks also informs the monitoring and adjustment steps of adaptive management and, thus, is essential to learning (4).

5) Nonlinearity and tipping points. Complex systems faced with disturbance, such as climate change, may shift into another system state and that shift may be difficult to reverse (4, 30, 32, 40, 41). Governance focused on optimization of engineered infrastructure rather than managing resilience may lack the space to adapt, pushing systems closer to tipping points (40, 42, 43). Government resources and leadership are needed to move SETs farther from a tipping point or to facilitate equitable transformation (40, 42).

6) Uncertainty. Uncertainty is a product of the other five attributes of complex systems and becomes increasingly problematic for governance when a system is undergoing change (30, 44). Complex systems are inherently unpredictable, and as a result governance must recognize not only different types of uncertainty but also develop new institutions to manage, navigate, and resolve such unknowns.

Applying complexity science to the study of SETs emphasizes that top-down design of government programs is not adequate to manage the emergence, uncertainty, and nonlinearity of complex systems undergoing change. With self-organized adaptive governance already emerging in response to that inadequacy, the new focus of government must be to facilitate and steer the emergent response.

This new focus requires a new perspective on the role of government in society. Social systems, including market as well as regulated activities in economic systems thrive in a stable environment; legal systems are designed to support that stability (33). However, both the attributes and empirical studies of SETs from multiple disciplinary perspectives describe patterns of stability and increasing complexity (8, 9), followed by instabilities (including collapse and transformation) in response to both ecological and technological change (8, 43). What is different today that requires specific attention to the attributes of complexity is the pace of change, the degree of social, ecological, and technological interconnection, and the coevolutionary dynamics of interdependent systems when prescribing policy solutions (26). Governance must help society navigate and steer society through such rapid evolutionary transitions. Law and government are integral to that process.

Viewing Governance through the Lens of Complexity

To assist a society undergoing accelerating change, legal systems must account for emergent responses to the attributes of complex systems. No single entity, public or private, can orchestrate the response to the surprising, multiscale nature of complex emerging problems in SETs. Self-organizing adaptive governance efforts emerge at multiple scales, providing the functional and response diversity referred to as polycentricity (7) and increasing the likelihood of innovation through diverse experimentation at multiple scales.

Scholarship on emerging forms of governance in response to complexity in SETs has focused on the complexity attributes, their relation to system complexity, and concerns with potential impacts on social equity (21). Empirical observation and theoretical development of the concept of "adaptive governance" comes from the literature on governance of social–ecological systems (SES), with theoretical foundations in resilience and sustainability (9, 13, 36, 39). Coincident with this work on SES governance, political scientists who study globalized economic systems and view relationships in these systems through the lens of power have observed and theorized the development of "new governance." The emergence of similar governance patterns in different social sectors across multiple levels of governance and convergence in the understanding of their structure and function from different disciplines suggests that broader phenomena are at play, including response to system complexity.

Adaptive governance is described in the context of human interaction with the environment. In western democracies, this is an area in which law and government have focused on a regulatory approach since the 1960s. Adaptive governance is thought to emerge in response to the unintended consequences of one-size-fits-all regulation, competing sectoral goals, scarcity, and increasing interdependence of system components (11, 36, 39). New governance is described in the context of public services and the economy. It refers to the increasing role of nonstate actors in the delivery of public services and the self-organization of nonstate actors in response to frustration with the unintended consequences of the neoliberal reforms of the 1980s and 1990s, including deregulation and overreliance on markets (8, 45).

New governance and adaptive governance both include as essential features bottom-up self-organization and collaboration; public, private, and public–private networks; and multiple nested centers of authority (i.e., polycentricity) (6, 8, 10, 11, 36, 39, 45, 46). Adaptive governance literature calls out the presence of processes to manage uncertainty and mechanisms for learning and incremental adaptation (4, 10, 11, 36, 37, 39, 47). Both emergent forms of governance respond to increased connectivity and complexity and the corresponding need for contextualization and adaptation. They appear able to navigate and maintain overall social stability when system trajectory is uncertain and fraught with surprise (8, 10, 11, 36, 39). In short, they represent societal responses to complexity.

Governing Complexity

While current theoretical and empirical work suggest that emergent forms of governance may be promising in addressing complexity (9, 11), emergence is ad hoc and is not occurring fast enough to adapt or transform at the rate of change that characterizes the Anthropocene. Any attempt to accelerate response through intentional action must take into account the list of attributes of complex systems. This requires governance that allows for adaptation and transformation without destabilizing society as a whole (recognizing that localized destabilization may be a prerequisite to transformation) (21, 33). Society can employ legal systems to facilitate and operationalize innovations in governance, including adaptive (10, 36, 39) and transformative (42) governance of SETs undergoing change and to steer them toward the public good.

It is also increasingly recognized that the ad hoc formation and the individual motives of private actors may lead to increasing inequity in access to decision-making and inequality in the results of adaptive governance (8, 9), raising the question of how governance itself is governed. To address this issue, we analyze the role of government in steering emergent processes toward the public good, and turn to the legal processes that manage legitimacy (including transparency and accountability) (48), access to decision making (also referred to as "participatory capacity") (21, 37), responsiveness (49), equity, and justice (38).

Government as Facilitator. Collaborative processes, when accountable to clear government-established goals, can lead to innovative solutions that resolve tradeoffs among stakeholders and link local and indigenous knowledge to the biophysical system, allowing tailoring to the emergent results of complexity (50, 51). This incorporation of other ways of knowing has been observed despite emergence within western systems of science and government (52). Without government facilitation, an emergent collaborative might never have the resources (i.e., financing, knowledge, workforce, and social capital) to develop and test new ideas. Without government steering, emergent governance will not necessarily act in the public good [e.g., Al Qaeda is considered a "dark network" of emergent governance (53)]. Without the scientific input (discussed in the next section), the collaborative may never develop a process of learning that allows it to adapt as the system changes.

In a complex SETs commons (Fig. 1), regulatory mechanisms can be helpful but are often insufficient. In fact, conflicting regulation may catalyze self-organization (11) and may be designed to support experimentation (54). To facilitate adaptive governance, centralized governments may also need to set societal goals, while using incentives such as subsidies, tax breaks, public procurement, and research funding, to support experimentation (54) to steer nonstate governance actors toward those goals. Such an approach may catalyze the bottom-up emergence of public or private governance systems, as well as build capacity to address problems at a more localized level. Government-as-facilitator may cultivate cross-sectoral integration (e.g., between food, energy, and water sectors) as well as coordinate cross-jurisdictional (e.g., among multiple local governments, or regional government and tribes) and public–private networks (e.g., among state actors and corporations that cross international boundaries) that are needed to address complex problems (46).

The role of facilitator must be tiered with increasingly structured and higher-level leadership as the rate, risk, and scale of the new problems intensify. Thus, a pandemic or sea level rise may require leadership and clear policies from federal level as well as resources to build local capacity, whereas increasing water temperatures due to climate change may require local input to goal setting and a tailored response to mitigate impacts on temperature-dependent aquatic species.

For resilient solutions during periods of accelerating change, government must provide continuity to smooth transition as private sector interests innovate. During stable periods, incremental policy changes will continue at a slower pace (55). Viewing governance of complex systems as a complex system itself underscores the need for adjustment and mechanisms to evolve based on feedback on policy efficacy and changing social values. In legal terms, this requires judicial review to move from the initial stages of planning to the evolving stages of implementation, and that the basis for review be measured by progress toward goals rather than predicted outcome (45).

The integration of new governance literature also helps address the weakness in the adaptive governance literature—namely, the failure to address agency, power, and empathy (9, 28, 29). Literature on new governance expresses concerns with the weakening role of the state and the corresponding increasing role for private actors in public governance, a formula that may result in lack of attention to the attributes of legitimacy, equity, and justice, that is only recently seeing uptake in the adaptive governance literature (8, 9, 55). Those expressing concern look to an increase in the role of government primarily through legal systems (8, 37, 43, 55).

Government as Manager of Legitimacy, Equity, and Justice. Value-based attributes of western democracies—including legitimacy [defined in law to include processes that manage transparency, accountability, access to decision making, as well as the democratic processes of deliberation and voting (48)], equity, and justice—can be undermined by ad hoc, private processes influencing allocation of common pool resources, provision of public services, globalized economies, and protection of public health (8, 21). Where government is absent or ineffective, interests may be left out, delay tactics by those benefiting from the status quo may postpone solutions, local processes may be captured by powerful interests, and highly innovative solutions stifled. Legitimacy is threatened when only powerful interests have the resources to participate. Equity is threatened when there are no checks on who bears the burden of change, and who receives resources for adaptation and transformation. Justice is threatened when there is no means to address corruption and provide review for failure to meet the goals.

As a preliminary matter, it is important to understand the limits of law in providing for legitimacy, equity, and justice. It goes too far to suggest that government can be the "ensurer" of legitimacy, equity, and justice, but it is insufficient to say that it can be only a "promoter." We use the word "manager" to suggest an active role, but one that lacks total control on outcomes. The reality of democratic systems of governance is that the best such systems can do is to establish and maintain the governmental (i.e., legislative, executive, and judicial) processes to provide legitimacy, equity, and justice. The role of law in this effort is to set the stage for the best possible outcome from emerging adaptive governance and keep it in place while adaptation and transformation unfold. To be sure, such rules are only as good as the ethics of those in power, but the fact that agency and power may act as the "trickster" and upset all the best-laid plans for legitimacy, equity, and justice is no reason to avoid setting the stage with the most carefully crafted rules possible. As Sir Winston Churchill (56) is said to have stated, "it has been said that democracy is the worst form of Government, except for all those other forms."

With even the current adaptive mechanisms of democratic governments, society has the capacity to incrementally address its failures in legitimacy, equity, and justice. Thus, for example in the coming years in the United States, society may consider changes to campaign spending that prevent one person/one vote from distortion by wealth; erect barriers to nepotism; revisit ethics rules for those in office; reform policing and mental health intervention, increase public education on civic responsibility, set up a bipartisan commission to present a short list of highly qualified people for appointment to federal courts, develop a new measure of GDP that reflects wealth distribution, establish clear national lines on pandemic response and develop redundancy within the tools and technology needed for that response; and reinvest in education and economic development in rural and marginalized communities.

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Then democracy will fail again, but in a different way. As Martin Luther King Jr. stated, "the arc of the moral universe is long, but it bends toward justice" (57). The best we can do is to offer laws that, when used responsibly, will further that trajectory.

The tools available to increase the likelihood of legitimacy, equity, and justice lie within the processes and curbs on corruption established by the legal system. With these tools, ethical leaders exercising agency, power, and empathy have a greater chance of achieving legitimacy, equity, and justice, and the people—the ultimate source of democracy—have a better chance of recognizing corruption when it occurs. The ability of society to effect these changes, or not, is thus, both the strength and weakness of democracy. To attempt to "ensure" that will occur is to subvert the very democracy we seek to inform.

In democratic governments, legitimacy, equity, and justice are promoted through the structural allocation of authority in constitutional law that provides for checks and balances (46), and the careful procedural design found in the regime of administrative law that dictates the process of government. Administrative law includes requirements for open records, open meetings, public comment, and judicial review (48). Administrative law governing process, however, does not generally apply to nongovernmental processes. With the addition of the unevenly distributed agency and power of nonstate actors in emerging governance, government must develop safeguards with 1) mechanisms that influence private action; and 2) means to promote equity in access to decision making and equitable distribution of its benefits (9, 21, 55).

Government may use incentives to influence private actions. Thus, for example, it may promote transparency through requirements placed as conditions on the contribution of public funds in contracts for private delivery of public services. Government may, through regulatory law, control funding, establish monitoring and reporting requirements for private actors in governance, and provide access to court when actors fail to report or provide equal access to participation. By requiring public access to reporting, government may hold private actors accountable when they formulate governance solutions. To safeguard the public good, it remains the role of government to set goals. However, in the face of uncertainty, government cannot simply provide upfront review and approval of a plan designed to achieve certain government established goals. Instead, accountability must be measured by monitoring progress toward goals as innovative solutions with uncertain outcomes are attempted. In the face of irreducible uncertainty, comprehensive planning will not provide the needed information, and may lock in decisions that turn out to be less than optimal or based on mistaken assumptions. Instead, accountability must be provided by transparently monitoring progress (44). Finally, government must play a leadership role in mediating competing private interests to promote legitimate settlement of disputes and equitable outcomes.

These measures, however, do little to address the problem increasingly recognized as a secondary impact of the growth in private governance—inequity in access to decision making, and inequality in the distribution of benefits (9, 36, 55). Tax laws have been the traditional source of redistribution of wealth in democratic societies. But we agree with Clark and Harley (9) that a bottom-up process of capacity building in marginalized and impoverished communities is needed to address not only wealth inequality, but inequality in education, knowledge, access to decision makers, and time to participate. Cosens et al. (37) characterized this as the role of law and government in building "participatory capacity."

New Institutions for Governing Complexity

Learning in a way that can cope with the need for dynamic governance requires both changes in education and a new focus in the science of SETs. While the need for interdisciplinary research has long been considered important to inform complex governance decisions, gaps exist in addressing the complex interaction between governance and SETs as coevolving systems. As noted by Fazey et al. (ref. 58, p. 5, emphasis added), we "need to go beyond producing knowledge *about* our world to generating wisdom about *how to act within it*." In addition, within rapidly changing systems the quest for knowledge transferability in space must be supplemented by transferability through time to place system evolution within its complex historic context, thereby creating a deeper understanding of its trajectory. To fill these gaps, we suggest 1) the establishment of long-term, integrated, and transdisciplinary study programs to address the complexity of the coevolution of governance and SETs over time (long-term social–ecological–technological study areas [LT-SETs]); and 2) training within LT-SETs for new types of professionals with knowledge of governance, law, and science of SETs who can help navigate uncertain futures by developing wisdom and understanding. In advancing these ideas, we acknowledge that the establishment of LT-SETs and education of transdisciplinarians would also benefit from the work of those who study how science and society coevolve to produce knowledge (59) and from those in science and technology studies who study how knowledge emerges within the society and culture it is situated in (60). In line with the science and technology studies literature, we acknowledge that assuming a systems perspective on SETs is not free of normative implications for knowledge production and governance. A deeper critical analysis of the epistemological challenge concerning systems perspectives in general and LT-SETs in particular is beyond the scope of the disciplines involved in this study, but we would welcome collaboration on this in the future.

LT-SETs. To address sustainability challenges, Norström et al. (61) call for coproduction of knowledge that 1) addresses the context in which the research takes place; 2) recognizes different ways of knowing, including indigenous and local knowledge; 3) is based on clearly articulated shared goals; and 4) allows for ongoing interaction among researchers and those living in and making decisions affecting the relevant setting. This list describes what has come to be known as "transdisciplinary" research (9, 29, 46, 62, 63), and is essential to the type of learning necessary for governance of SETs in a time of accelerating change. The complex commons (Fig. 1) requires transdisciplinary research in which scientists work with civil society, economic actors, NGOs, and policymakers to build capacity for contextualized understanding of emergent system response to both policy and action.

A framework of single-, double-, and triple-loop learning within governance regimes (Fig. 2) is useful for understanding the participatory feedback needed to integrate understanding of coevolving governance and SETs (49). Single-loop learning requires coproduction of system understanding and management design followed by monitoring and incremental adjustment. This resembles adaptive management (4). But research into learning for governance should go beyond management. The necessary double- and triple-loop learning require knowledge of the policy and social sciences to ask not only what is technically feasible, but what is humanly acceptable and does that alter our underlying assumptions? Questions of social, political, and legal feasibility of different management options must be part and parcel of the learning
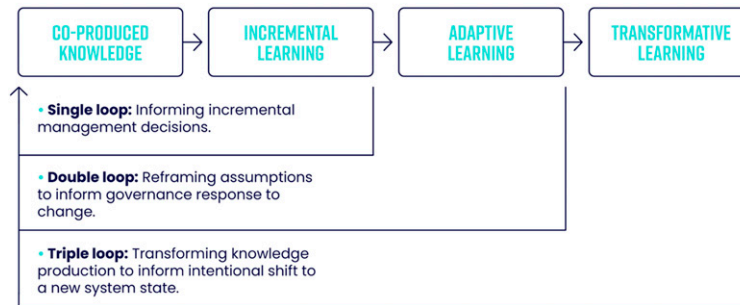
Fig. 2. Triple-loop learning in the context of governance. The concept of triple-loop learning is adapted from Pahl-Wostl (49).

process. Coproduction of knowledge may help shift the dialogue and reveal more options than currently thought available. Understanding the availability of multiple options is essential because the desire for stability provides a false sense of security in the face of accelerating change and favors the status quo. Coproduction of knowledge may be one way to break that path dependency.

Disciplinary sciences that reduce the biophysical environment into component parts remain critical in generating knowledge, yet they struggle with the emergent properties, chaotic dynamics, and uncertain outcomes of complex systems (64). Empirical observations as well as high-speed computing and big data are helping to generate actionable complexity science, yet they struggle with SETs integration and the addition of governance due in part to the roles of agency and power. Long-term integrated study that uses incremental learning over time within a specific participatory context can help generate knowledge on how to manage this complexity. This requires deep understanding of individual SETs and governance through time with the long-term engagement of society.

Nevertheless, this proposal for LT-SETs must address the fact that place-based transdisciplinary research runs the risk of being dismissed as mere case studies lacking the generalizable knowledge so essential to the funding and publication goals of academic researchers. Consider, however, that the focus on geographic transferability (e.g., studying salmon in the Pacific Northwest of the United States and Canada may generate knowledge useful for the study and management of salmon in Finland) is too limited for the Anthropocene. What about transferability through time? In a complex system undergoing change, adaptive research to inform adaptive governance must build on its own mistakes and successes as a specified system evolves, deepening understanding of the system and how its governance handles change. Aspects of the process of adaptive governance may be transferrable geographically as the transdisciplinarians described below enter the workforce, while the substance of the LT-SETs research will be valuable through time.

Questions aimed at understanding coevolution of SETs and governance are as much questions of science as they are of policy, and they will not be answered if the two domains do not achieve a greater level of integration both at the individual level and at the level of knowledge-producing communities (scientific, but also local and traditional communities). Thus, increased focus on incremental understanding of SETs through time and on building long-term relationships among the scientists and other knowledge producers, affected civil society, management institutions, and policymakers also requires a new approach to education. Such an approach places

significant emphasis not only on integrating different kinds of knowledge and ways of knowing but also on strategies and methods for managing diverging visions of the future in a complex SETs. Here, it is crucial that the transdisciplinarian knows the legal boundaries and opportunities for navigating adaptive governance through complexity in a way that is legitimate, equitable, and just.

Applied Transdisciplinarians. Calls for funding for interdisciplinary scientific research for the grand challenges facing a society remain critical today (65), but we also need a new type of scientific practice—scientists trained to do transdisciplinary work at the science–policy interface. While some agency, NGO, and industry scientists as well as some academic researchers already practice at this interface and many now take courses on science communication and science for policy, all of which are important, we currently lack training for people who have the skills to develop deep understanding of the coevolution of governance and SETs. This understanding requires training graduate transdisciplinary students in a governance process and can be accomplished by educating them within an LT-SETs.

Consider, for example, forging a field of public ecology in which the scientists and scientific teams trained in transdisciplinary systems must understand as much about the social, legal, and policymaking systems as the ecological systems. They must not only understand the differences in natural and built systems and their context-specific interaction, but that place-based differences in culture, norms, and history lead to differences in institutions, the perception of science, and the capacity to act (8, 29). This concept goes beyond the field of conservation biology in which the researcher chooses to do research that furthers the conservation of species and the ecosystems they rely on. It does so by developing a methodological field of science in which the goals of research and the research questions are coproduced with those dependent on and managing SETs, and in which the research questions are about the interplay and feedbacks among governance, infrastructure, and a specific ecosystem. This type of research requires comfort with experiments designed to be incrementally adjusted based on feedback from monitoring of the natural, built, and social systems.

Training such scientists will require the following: new programs that bring together educators, practitioners, and managers from the natural, policy, and social sciences, engineering, and law; incentives—including tenure criteria and peer review—that acknowledge the value of integration and participatory research;

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and funding and publication venues interested in the long-term understanding of coevolving systems.

By increasing our understanding of the systemic behavior of coevolving governance and SETs, cocreating that research with those making decisions over time, and training a new type of scientist at the evolving intersection of science and governance, the knowledge of process and the messy science–policy interface produced in an LT-SETs becomes transferrable to other settings. In this way, the stage will be set to accelerate innovative governance responses to change in the Anthropocene while preserving the values of legitimacy, equity, and justice.

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