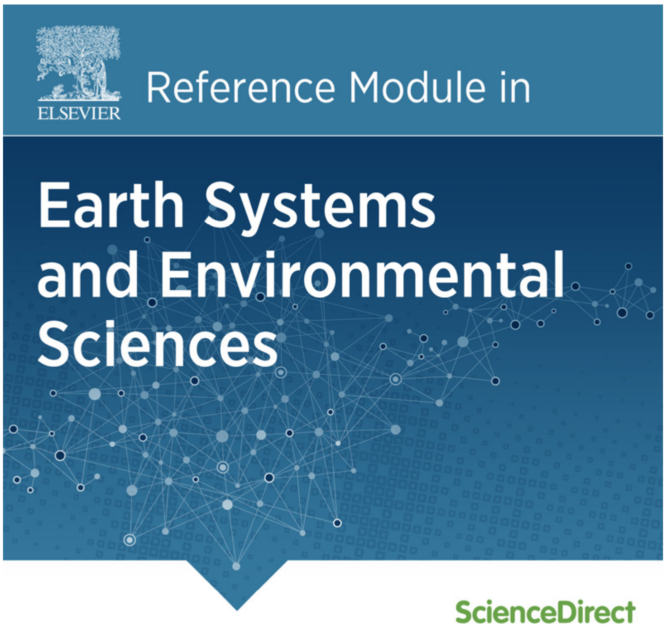

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Socioecological Systems☆

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Socioecological Systems (SESs)

There are no social systems without nature, and few ecosystems without people, such as some large wilderness areas, recognizable for their intactness and for the very low population density. An area must retain at least 70% of its historical habitat extent (500 years ago) and five people per km^2 to be considered a wilderness area, and at global level they are represented by five areas: Amazonia, Congo, New Guinea, the Miombo–Mopane woodlands, and the North American deserts. In the case of oceans, the marine pelagic environments are characterized by some areas free of human influences, even if resource competition due to human exploitation of prey species can cause both nutritional stress and negative behavioral changes in pelagic predators.

Systems where social, economic, ecological, cultural, political, technological, and other components are strongly linked are known as socioecological systems, emphasizing the integrated concept of the 'humans-in-nature' perspective. Socioecological systems (SESs) are truly interconnected and co-evolving across spatial and temporal scales, where the ecological component provides essential services to society such as supply of food, fiber, energy, and drinking water. As a result, socioecological systems have become an emerging focus in scientific and policy arenas.

Landscapes change constantly from natural and anthropogenic drivers, and land use and land cover changes by humans have been identified as a primary effect of humans on natural systems. These changes underlie fragmentation and habitat loss, which are the greatest threats to biodiversity and ecosystem services. The complex interactions between development decisions and ecosystems, and how the consequences of these decisions may then influence human values and subsequent decisions is an important area of research interest.

Given the results of the Millennium Ecosystem Assessment, reciprocal influences among humans and the climate, biota, and ecological goods and services of the world have become both stronger and more widely recognized. In this context there has also been the acknowledgment that in the majority of ecosystems, structure and function are now determined primarily by human interactions, perceptions, and behaviors, so that nowadays it is more appropriate to think of socioecological systems combining approaches from both environmental and social sciences.

The socioecological system theory sprang from the recognition of close interaction between society, in terms of social–economic system, and natural system. For this reason, an interdisciplinary approach is needed: in the past the social–economic approach was distinct from that of ecology; the stereotypical economist might say 'get the price right' without recognizing that price systems require a stable context where social and ecosystem processes behave 'nicely' in a mathematical sense – that is, they are continuous and convex. The stereotypical ecologist might say 'get the indicators precise and right' without recognizing the surprises that nature and people inexorably and continuously generate. These simple approaches are often attractive because they seem to replace inherent uncertainty with the fictitious certainty of ideology or precise numbers. But the theories implicit in these approaches ignore multistable states that characterize SESs.

SESs show a complex and uncertain nature rooted in the complex systems theory that refers to interrelated theories (catastrophe theory, chaos theory, information theory, hierarchy theory, and self-organization theory) that have originated from different scientific disciplines. Despite their traditional scientific disciplinary origins, they have provocative implications across disciplines and fields and, more generally, for the way we understand various types of phenomena as well as the role of learning in planning and policymaking.

In the past, the usual way to study complex phenomena was based on simplifying them through analytical reductionism (describing them as simple systems, machines) or by aggregating and averaging through statistical analysis (describing them as unorganized complex systems). Since an SES is made up of many different parts that interact to form a more complex entity, its dynamic can be explored using an holistic approach because it does not focus on a detailed understanding of parts, but on how key

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components contribute to the dynamics of the whole system. But complex systems, such as SESs, exist at a threshold between order and chaos, because they are too complex to be treated as machines and too organized to be assumed random and averaged. An example could be the slow erosion of key controlling processes that can abruptly flip an SES into a different state that might be irreversible (the gradual loss of species important for pollination could cause the slump of an economy based on agricultural products).

It is relevant to understand the human sources of ecological change. To do this, we must understand the driving forces motivating human actions. Driving forces are the underlying causes that influence and direct human activities. These forces, either directly or indirectly, result in changes in ecosystems, which can degrade ecosystem capability to provide goods and services. The roots of these forces can be economic, political, sociocultural, and/or legal, and rarely occur in isolation, but rather act in conjunction with others. Direct driving forces, such as mining or agricultural practices, are easily recognizable as they often have an immediately discernible effect. Indirect driving forces are less identifiable; however, they have no less of an impact on ecosystems since they influence people's actions. For example, legislation can encourage people to mine rather than farm an area and influence how they will mine. There are several examples in the world: Britain's solution to rising urban pollution levels in the 1800s was to increase the height of factory chimneys. This only postponed the problem in England, while it then introduced problems in Scandinavia. This was only a temporary solution and only at the local scale. The source of the problems, the emissions from industrialization, remained unchanged in quantity or quality. In Europe, the WTO has required the end of European preferential treatment of some banana-producing nations. The opening of trade within the EU could drive land-use changes in other banana-producing countries. The WTO has certainly foreseen this possible outcome. However, it is simply considered a shift of production location based on economic considerations, disregarding both the social and ecological changes that can be driven by such a shift.

Human society is able to choose alternative development scenarios. Initiatives toward development might cause social and ecological changes and bring surprises and uncertainties. It is necessary to plan strategies that enhance system's adaptive capacity to change rather than simply maximize resource consumption. In the case of sweeping surprises, partial solutions, only economic, or social or ecological, bring the loss of benefits coming from the integration among economic, social, and ecological processes. The base of sustainable policies and investments should be turned toward knowledge integration, with the aim to obtain a comprehension based on different viewpoints.

Key Features of SESs

Complex systems theory offers a more sophisticated understanding of the structure and dynamics of both social and ecological systems than the relevant 'normal' scientific disciplines.

The properties of SESs are (Figure 1):

- *Nonlinearity*. They behave as a system and cannot be understood isolating their components.
- *Hierarchy*. They are hierarchically nested and the 'effect' exercised by a specific level involves a balance of internal (self-control) and external controls involving other hierarchic levels in a mutual causal way. Such interactions cannot be understood by focusing only on one hierarchical level (multiple scales of interest).
- *Internal causality*. This is due to self-organization.
- *Dynamical stability*. There are no equilibrium points for the system.
- *Multiple steady states*. There is not necessarily a unique preferred system state in a given situation, because multiple attractors can be possible in a given situation.
- *Catastrophic behavior*. It is typical of SESs, in terms of (1) bifurcations – moments of unpredictable behavior; (2) flips: sudden discontinuity; and (3) Holling four-box cycle. (exploitation – conservation – release – reorganization).
- *Chaotic behavior*. The human ability to predict the future is always limited.

The complexity of a system is the result of the interaction among a great deal of components that cause new, emergent, and unexpected properties. The analysis of these systems suggests that the possibility for a sustainable development depends on changing perception of human society regarding complex systems. Thus, an essential goal is to change the perception and the

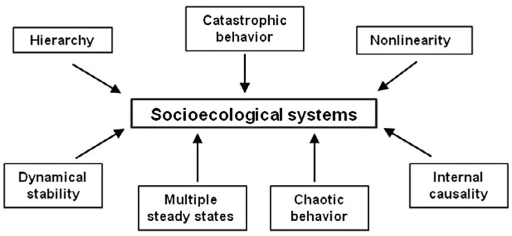

Figure 1 Characteristics of complex adaptive SESs.

Table 1 Key features of socioecological system structures and functions

Change	Change is episodic, with periods of slow accumulation of natural capital punctuated by sudden releases and reorganizations of biotic capital
Spatial attributes	They are neither uniform nor scale invariant. There are several different ranges of scales, each with different attributes of architectural patchiness and texture and each established and sustained by a specific set of abiotic and biotic processes
Stability domain	Ecosystems do not have a single equilibrium and homeostatic controls that keep them near it, rather, multiple equilibria commonly defining different functional states within the same stability domain
Policies and management	Policies and management that apply fixed rules, independently of scale, could lead systems to lose resilience

way of thinking of social actors, moving their attention from increasing productive capacity to increasing of adaptive capacity. This means that it is necessary to turn social actors' attention to a view where society and nature are coevolving in the biosphere.

SES theory was pioneered in the 1980s by the Resilience Alliance, a voluntary organization of scientists of various disciplines, to explore the SESs' dynamics and their possible evolutions, but there are several scientific schools interested in their study. These theories are based on concepts as adaptive cycles, resilience, adaptability, transformability, and hierarchy (panarchy), and aim to provide knowledge basis to manage complex adaptive systems and to achieve sustainable development in theory and in practice. The knowledge of these aspects should improve natural systems management and their capacity to support human and natural capital.

The novelty of these theories concerns natural, disturbed, and managed ecosystems, identifying which are the key features of ecosystem structures and functions (Table 1):

- Change is episodic, with periods of slow accumulation of natural capital such as biomass, physical structures, nutrients, punctuated by sudden releases and reorganizations of this biotic capital, as the result of internal or external natural disturbances, or human-imposed catastrophes. Rare events, such as hurricanes or the arrivals of invading species, can unpredictably shape system structure at critical times or location, leading to an increase in fragility. In this way, these rare events can modify the future of the systems for long periods, even if irreversible or slowly reversible states can exist; once the system flips into another state, only an explicit external management intervention could allow the system to come back to its previous self-sustaining state, but its full recovery is not assured.
- Spatial attributes are discontinuous at all scales, from the leaf to the landscape to the whole planet. There are several different ranges of scales, each with different attributes of architectural patchiness and texture and each established and sustained by a specific set of abiotic and biotic processes.
- Ecosystems do not have a single equilibrium and homeostatic controls that keep them near it, but rather multiple equilibria commonly defining different functional states within the same stability domain. Normal movements of state variables maintain structure, diversity, and resilience. Stochastic forces and interactions between fast and slow variables mediate the movements of variables among those equilibria.
- Policies and management that apply fixed rules (e.g., maximum sustainable yield), independently of scale, could lead systems to lose resilience, that is, systems break down in the face of disturbances that previously could be absorbed.

How Humans and Environment are Coupled: Examples

There are several examples on how human and environment systems are coupled and how human choices and the consequent environmental effects influence each other. The following are three examples regarding southern Yucatan, Arctic region, and Eastern Europe.

Southeastern Mexico retains parts of the largest continuous expanse of tropical forests in Middle America. One part of the 22 500 km^2 southern Yucatan peninsular region experienced extensive, state-led development beginning in the late 1960s, causing deforestation with consequences on human well-being. In this region, almost all farmers cultivate maize for subsistence and, increasingly, have undertaken commercial chilli production, giving rise to a fragmented landscape of opened and successional forest land. Increasing reliance on commercial chilli production has raised household income but simultaneously driven large swings in this income. This is because chilli is water, pest, and disease sensitive, and the price in the region is highly variable. At the same time, the area is characterized by two main environmental hazards: water stress and hurricanes. The natural land covers, seasonal tropical forests, are adapted to water stress, because they drop foliage during the dry season, while farmers respond to this stress by taking an early dry-season catch crop. On the other hand, severe hurricanes and subsequent dry-season fires knock down large stretches of forest that need a long time to regrow. Hurricanes arrive during the main harvest period, damaging crops, especially chilli, by winds, rain, and floodwater, because a fragmented landscape creates more forest edges exposed to severe winds, damaging near-edge trees. This more open landscape causes less wind protection for crops, with consequences on local economy and human well-being.

Environmental and social changes have had and are expected to have significant effects on coupled human–environment systems in the Arctic. The Arctic Monitoring and Assessment Program have stated that although the Arctic is a relatively clean environment, it continues to suffer from significant pollution hazards, especially with regard to heavy metals and persistent organic pollutants. At the same time, native Arctic peoples have also experienced significant social changes over the past three decades, establishing new relationships between local and national governments, becoming more closely connected to external markets and ways of life, and asserting their identity, rights, and culture in legal and policy forums. Three kinds of stressors interest the Arctic region: (1) climate change with consequences on snow cover, sea ice, and extreme weather events; (2) environmental pollution (potentially toxic organic compounds, acids, metals and radionuclides), some models used in the Scenarios Network for Alaska and Arctic Planning (SNAP) research took into account a steady increase in carbon dioxide emissions from fossil fuels combustion over the first several decades of the 21st century; and (3) societal trends in terms of consumption, governance and regulation, and markets. These represent threats to human health and well-being, indigenous cultures and food security, and human settlements and development. The Arctic region is an example of cross-scale systems interaction, because the decisions taken in different regions affect people living in the Arctic region: global market, climate change, and environmental pollution.

Traditional farming landscapes are an example of socioecological systems, since they are the result of the interaction and co-evolution over centuries between people, which shaped the land through their activities, and the nature that, in turn, gave people a variety of ecosystem services. Many rural communities in Japan, India, China, and Europe are characterized by a well-developed system of traditional ecological knowledge to assess the quality of the ecosystems goods and services and to sustainably manage natural systems; this resulted in landscapes with high aesthetic, ecological, and cultural values. However, these socio-ecological systems are rapidly changing due to the social, economic, cultural and institutional changes in the society. In fact, many traditional farming landscapes have come under pressure from by a large number of socio-economic challenges such as the growth of population, economic, industrial and infrastructural development, globalization. These changes have made traditional subsistence agriculture economically unprofitable and unable to meet the increased social demands, leading to landscape changes such as land-use intensification or land abandonment and eroding many valuable cultural and ecological elements as well the linkages between local communities and their ecosystems.

The History as a Basis for the Future of Socioecological Systems

The history of human-dominated socioecological systems is one of successive crises that were either successfully addressed, leading to sustainability, or not, leading to collapse, and the goal of studying history has always been to understand the past in order to understand and deal with the present and the future. The assessment of the vulnerability of modern socioecological systems to future human activities and climate change can be greatly improved by (1) knowing the rates and directions of past trajectories in key processes, such as land cover, soil erosion, and flooding; (2) defining and analyzing how thresholds have been transgressed in the past; and (3) deducing the natural or pre-impact patterns of environmental variability. Therefore, the past provides the means to test the models upon which we depend for future projections and scenarios. The present nature and complexity of socio-ecological systems are heavily contingent on the past; we cannot fully appreciate the present condition without going back decades, centuries, or even millennia.

The complexity theory, with related concepts such as nonlinear change, feedback and regime shifts, suggests that human activities and environmental change should be viewed together as a co-evolutionary and adaptive process. Positive feedback loops may lead to a conditioning of landscapes that makes them more sensitive to new perturbations. Hence, some historical societies, like those on Easter Island, became more prone to collapse through continuing resource depletion and ecological degradation. Others, such as the Akkadian society of Mesopotamia, became increasingly vulnerable to climate perturbations as their dependence on irrigated cultivation increased.

SESs' Management

Environmental management is another field of research and practice integral to any discourse on knowledge and social learning for environmental policy and decision making. A simple definition of environmental management states that it consists of "actual decisions and action concerning policy and practice regarding how resources and the environment are appraised protected, allocated, developed, used, rehabilitated, remediated, and restored." Much of current environmental management focuses on the integration of social and ecological systems, as our understanding of environmental issues has evolved. In this context, environmental decision making has to address the complexity of both ecological systems and interdependent human organizational and institutional systems. Several scholars have set a profound and necessary precedent with their work, explicitly integrating the study of natural resources with human organizations and institutions to focus research and intervention on integrated SESs. In recent decades, efforts to address some of the paradoxes in resource and environmental management have required an evolution in thinking about environmental science and decision making. The result has been a shift from reductionism, command and control science and management, to a more integrated, adaptive, systems-based approach. Integral to this more systemic approach to environmental decision making has been the incorporation of an emerging body of theory often referred to as complex systems theory.

Complex systems theory has offered a more sophisticated understanding of the structure and dynamics of both social and ecological systems than the relevant 'traditional' scientific disciplines. Even this integrated, systemic view of SESs does not explicitly acknowledge the complexity of the process of social learning for decision making within SESs. The integration of planning and governance theory with complex and critical systems thinking, as well as with social learning, points to new opportunities in the study of environmental decision making.

Attempts to extend insights from the field of social learning to the practice and study of resource and environmental management have also contributed to the discourse on social learning for environmental planning and decision making; for example, how public participation in environmental assessment processes provides opportunities for social learning.

Works in the field of environmental management have highlighted the importance of integrating social and ecological systems, highlighting the importance of social learning for the purposes of environmental decision making.

Governance is another main field of practice in which the linkage among knowledge, learning, and intervention in the context of environmental decision making is prevalent. Governance focuses directly on the political side of the decision making. There are several definitions of governance; however, all of these speak to a conception of political economy, and more generally decision making and knowledge for intervention, that is more broad-based, flexible, and evolving than traditional models of public decision making through government intervention.

Complex systems approaches could provide, and are already providing, governance stakeholders with philosophical and methodological underpinnings and practical heuristics to look critically at the interface of learning and intervention. The governance literature highlights the importance of politics and pluralism in decision making.

Existing Socioecological Systems Frameworks

An effective management and understanding of the different aspects of an SES needs the development of an integrated framework that considers the feedback and interactions between and within social, economic and ecological systems. There are several existing socioecological system frameworks that reflect the variety of research fields involved in the study of an SES and that can be applied according to the problem to be studied and the way in which the social-ecological system is conceptualized.

Among them, for example, the DPSIR (Driver-Pressure-State-Impact-Response) conceptual model is one of the framework that shows the cause–effect relationships between environmental and human systems and that has been used for analyzing and assessing the social and ecological problems of systems (above all aquatic systems) subject to anthropogenic influence.

The Millennium Ecosystem Assessment introduced a framework for analyzing SESs connecting drivers, ecosystem services and human well-being. In addition to ecological processes, also social factors such as skills, management regimes, and technology are involved in ecosystem services production. In particular, the framework makes more visible the links between the spatial and temporal provision of ecosystem services (supply) and the beneficiaries where corresponding well-being is appreciated (demand). For this reason the ecosystem service approach is very useful for a better understanding of ecological functioning, social structures, trade-offs and synergies between services, benefits on human well-being, and how these aspects feed back to influence governance and policy and, therefore, SESs and their services. As a consequence, this framework has considerable influence in policy and scientific communities supporting problem solving and proactive management.

A prominent and widely applied framework that focuses attention to socioecological systems is the vulnerability framework that provides the broad classes of components (exposure, sensitivity, resilience) and linkages that comprise a SES's vulnerability to multiple environmental and human changes and hazards. Vulnerability is a highly complex phenomenon with both biophysical (e.g., climatic conditions, natural hazards, topography, land cover) and socio-economic (e.g., demography, poverty, trade, employment, gender, governance) factors that determine its sensitivity to any set of exposures and influence the potential for harm. For this reason, the framework considers linkages to the broader human (social/human capital and endowments) and environmental (natural capital/biophysical endowments such as soils, water, climate, minerals, ecosystems) conditions and processes operating on the SES under study. These conditions can influences the responses (coping, impacts, adjustments, and adaptation). In particular, the social and biophysical responses or coping mechanisms influence and feed back to affect each other, so that a response in the human subsystem could make the biophysical subsystem more or less able to cope, and vice versa.

Another general framework called social-ecological system framework, conceptualizes that each of the individual SESs is composed of four core first-level subsystems: resource systems (e.g., coastal fishery, protected area), resource units (lobsters, wildlife), users (fishers, tourists), governance systems (organizations and rules that govern fishing on that coast, management authority of protected area). Each core subsystem is divided into lower levels made up of multiple second-level variables (e.g., size of a resource system, level of governance,) which are further composed of deeper-level variables. These subsystems are relatively separable but interact and affect each other to produce outcomes at the SES level, which in turn feed back to affect these subsystems and their components, as well other larger or smaller SESs. The framework is useful to identify the multitier hierarchy of variables for analyzing and understanding the functioning of an individual SES and the reasons why certain e.g. management actions and particular policies enhancing sustainability and succeed in one SES and fail in another. This framework has been applied above all for explaining sustainable outcomes in the context of forestry, fishery, and water resources.

SESs and Social Learning

The literature on social learning attempts to make operational many of the complex epistemological issues around the nature of knowledge and the process of learning.

A useful and less theoretical definition underlines that "social learning means more than merely individuals learning in a social situation . . . (they) envision a community of people with diverse personal interests, but also common interests, who must come together to reach agreement on collective action to solve a mutual problem. . . it is the process by which changes in the social condition occur – particularly changes in popular awareness and changes in how individuals see their private interests linked with the shared interests of their fellow citizens." Social learning is intended to help improve the quality and wisdom of the decisions when faced with complexity, uncertainty, conflict, and paradox, and the notion has begun to be applied in a variety of complex decision-making contexts, including environmental management and planning. Environmental planning and management are often described as complex and highly uncertain and, from this perspective, management cannot be seen as the search for an optimal solution to a single problem but rather as an ongoing process of adaptation, learning, and negotiation. Thus, to manage complex adaptive systems, it is necessary to create a learning atmosphere, encourage systemic thinking about complex problems, discourage competitive behavior among stakeholders, and focus on 'desirable and feasible change' rather than attempting to achieve absolute consensus on management issues. An example is given by the application of social learning to river basin management, considered as the capacity of different authorities, experts, interest groups, and the public to manage their river basins effectively. Often, limitations of existing institutions, to consider multiscale, participatory forms of governance for groups involved in river basin management are present. These applications show that social learning processes can improve stakeholders' awareness and participation in environmental deliberation and decision making and therefore contribute to practical change in environmental management as well as institutional change.

Social Adaptive Responses to Ecosystem Change

Despite the lack of theories linking the creation of ecological knowledge from observations and understanding to its incorporation into resources use, Figure 2 provides a conceptual model of possible responses to a crisis situation. In this context, the term crisis broadly refers to a large perturbation, and it may be human made (resource collapse) or natural (hurricane).

Three generic responses are possible when a crisis occurs:

(1) no effective responses;
(2) response without experience, in which the institution, a government agency or an informal local management institution, responds to a crisis but does not have previously tested policies, with accumulated ecological knowledge, at its disposal; and
(3) response with experience, in which the institution has previous experience with a crisis of that kind and management policy used on previous occasions.

In centralized and bureaucratized management systems, the 'no effective response' is the management reaction that often characterizes brittle or fragile institutions. Such a response allows accumulating up the panarchy (a hierarchy of socioecological systems), creating the conditions for a larger-scale crisis, both political and ecological. Response without experience is a frequently seen reaction to a crisis, and it could lead to institutional learning. This is the case in which the crisis is a true surprise, so that the institutions will have no previous experience with it, or the crisis may have been predictable but be of magnitude that had never been experienced in that area.

The response with experience is possible if the memory of the experience provides a context for the modification of management policy and rules, so that the institution can act adaptively to deal with the crisis.

The more useful management to be applied to SESs is adaptive management, and the more useful assessment is based on the integration of different disciplines.

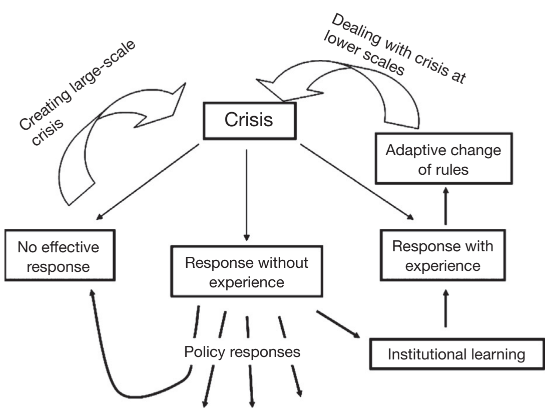

Figure 2 Three generic responses to resources and environmental crisis. Most responses fall into categories of (1) no effective response, which can lead to larger-scale surprises; (2) reacting with no memory or experience; or (3) responding through learning.

Adaptive management needs to at least maintain political openness, but usually it needs to create it. Consequently, adaptive management must be a social as well as scientific process. It must focus on the development of new institutions and institutional strategies just as much as it must focus upon scientific hypotheses and experimental frameworks. Adaptive management attempts to use a scientific approach, accompanied by collegial hypotheses testing to build understanding, but this process also aims to enhance institutional flexibility and encourage the formation of the new institutions that are required to use this understanding on a day-to-day basis.

Adaptive management approach needs the definition of SESs' boundaries encompassing multiple spatial scales of socio-ecological processes and engaging a variety of stakeholders to ensure that management interventions and policy strategies could reflect many different socioecological values and viewpoints. Moreover, since institutions, policies and goals are established over a particular time, they need to be continuously monitored, assessed, and re-evaluated or adapted, as circumstances change, knowledge about the SES is increased and learning takes place.

Conclusions

The SES theory recognizes that human dimension shapes and is shaped by environment, so that social and ecological systems are interconnected and coevolving across scales. Since both social and ecological systems are dynamical, the associated policies, including economy that represents the main driver, have to be dynamical; governance systems based on policies that try to control few ecological processes (command and control) do not allow the sustaining of the capacity to deal with change, producing fragile SESs.

A central aspect in dealing with SESs is that they are characterized by cross-scale interactions, both temporal and spatial, and the same is applicable to their governance, because decisions taken at one place in the past and in the present can affect people currently or in the future living elsewhere. The approach used to dealing with SESs assigns surplus value to a social system that clears the limits of sociological approach. In this perspective, social system includes also economic, institutional, and management aspects, by setting the rules. This gains in importance because, according to the 'tragedy of the commons,' the prediction is that in the absence of rules governing who can use natural resources (open access), individual users pursue their own interests, as in the case of ecosystem goods and services.

Since systems are uncertain and complex, the management needs to be flexible and adaptive, recognizing that it is impossible to control so many variables. Strategically, the only way to manage SESs is to adopt a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs, by evaluating alternative hypotheses about the system being managed.

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