it can address the inherent heterogeneity in who meets whom. This application can be extended to social networks as a way to estimate the spread of disease (30) and the evolution of cooperation (31) in heterogeneous societies.

Conclusions

Networks are useful descriptors of ecological systems that can show the composition of and interactions between multiple elements. The application of networks to ecosystems provides a conceptual framework to assess the consequences of perturbations at the community level. This may serve as a first step toward a more predictive ecology in the face of global environmental change. Networks are also able to introduce heterogeneity into our previously homogeneous theories of populations, diseases, and societies. Finally, networks have allowed us to find generalities among seemingly different systems that, despite their disparate nature, may have similar processes of formation and/or similar forces acting on their architecture in order to be functional. Although we have only begun to understand how changes in the environment affect species interactions and ecosystem dynamics through analyses of simple pairwise interactions, network thinking can provide a means by which to assess key questions such as how overfishing can cause trophic cascades, or how the disruption of mutualities may reduce the entire pollination service within a community (25). As the flow of ideas among seemingly unrelated fields increases (a characteristic attribute of research on complex systems), we envision the creation of more powerful models that are able to more accurately predict the responses to perturbations of food webs, a major challenge for today’s ecologist.

References and Notes

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PERSPECTIVE

A General Framework for Analyzing Sustainability of Social-Ecological Systems

Elínx Ostrom1,2*

A major problem worldwide is the potential loss of fisheries, forests, and water resources. Understanding of the processes that lead to improvements in or deterioration of natural resources is limited, because scientific disciplines use different concepts and languages to describe and explain complex social-ecological systems (SESs). Without a common framework to organize findings, isolated knowledge does not cumulate. Until recently, accepted theory has assumed that resource users will never self-organize to maintain their resources and that governments must impose solutions. Research in multiple disciplines, however, has found that some government policies accelerate resource destruction, whereas some resource users have invested their time and energy to achieve sustainability. A general framework is used to identify 10 subsystem variables that affect the likelihood of self-organization in efforts to achieve a sustainable SES.

The world is currently threatened by considerable damage to or losses of many natural resources, including fisheries, lakes, and forests, as well as experiencing major reductions in biodiversity and the threat of massive climatic change. All humanly used resources are embedded in complex, social-ecological systems (SESS). SESs are composed of multiple subsystems and internal variables within these subsystems at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, cells of proteins, etc. (1). In a complex SES, subsystems such as a resource system (e.g., a coastal fishery), resource units (lobsters), users (fishers), and governance systems (organization and rules that control fishing on that coast) are relatively separable but interact 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.

Scientific knowledge is needed to enhance efforts to sustain SESs, but the ecological and social sciences have developed independently and do not combine easily (2). Furthermore, scholars have tended to develop simple theoretical models to analyze aspects of resource problems and to prescribe universal solutions. For example, theoretical predictions of the destruction of natural resources due to the lack of recognized property systems have led to one-size-fits-all recommendations to impose particular policy solutions that frequently fail (3, 4).

The prediction of resource collapse is supported in very large, highly valuable, open-access systems when the resource harvesters are diverse, do not communicate, and fail to develop rules and norms for managing the resource (5). The dire predictions, however, are not supported under conditions that enable harvesters and local leaders to self-organize effective rules to manage a resource (6). The special issue of Science is dedicated to the study of social-ecological systems (http://www.sciencemag.org/science/vol325/issue5960/). A general framework is used to identify 10 subsystem variables that affect the likelihood of self-organization in efforts to achieve a sustainable SES.

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or in rigorous laboratory experiments when subjects
can discuss options to avoid overharvesting (3, 6).
A core challenge in diagnosing why some
SESSs are sustainable whereas others collapse is
the identification and analysis of relationships
among multiple levels of these complex systems
different spatial and temporal scales (7–9).
Understanding a complex whole requires knowl-
edge about specific variables and how their com-
ponent parts are related (10). Thus, we must learn
how to dissect and harness complexity, rather
than eliminate it from such systems (11). This
process is complicated, however; because entirely
different frameworks, theories, and models are
used by different disciplines to analyze their parts
of the complex multilevel whole. A common,
classificatory framework is needed to facilitate
multidisciplinary efforts toward a better under-
standing of complex SESSs.
I present an updated version of a multilevel,
nested framework for analyzing outcomes achieved
in SESSs (12). Figure 1 provides an overview of
the framework, showing the relationships among
four first-level core subsystems of an SESS that
affect each other as well as linked social, eco-
nomic, and political settings and related eco-
systems. The subsystems are (i) resource systems
(e.g., a designated protected park encompassing
a specified territory containing forested areas,
wildlife, and water systems); (ii) resource units
(e.g., trees, shrubs, and plants contained in the
park, types of wildlife, and amount and flow of
water); (iii) government systems (e.g., the govern-
ment and other organizations that manage the
park, the specific rules related to the use of the
park, and how these rules are made); and (iv)
users (e.g., individuals who use the park in diverse
ways for sustenance, recreation, or commercial
purposes). Each core subsystem is made up of
multiple second-level variables (e.g., size of a
resource system, mobility of a resource unit, level
of governance, users’ knowledge of the resource
system) (Table 1), which are further composed of
deeper-level variables.
This framework helps to identify relevant
variables for studying a single focal SESS, such as
the lobster fishery on the Maine coast and the
fishers who rely on it (13). It also provides a
common set of variables for organizing studies
of similar SESSs such as the lakes in northern
Wisconsin (e.g., why are the pollution levels in
some lakes worse than in others?) (14), forests
around the world (e.g., why do some locally man-
aged forests thrive better than government-
protected forests?) (15), or water institutions (e.g.,
what factors affect the likelihood that farmers will
effectively manage irrigation systems?) (16). With-
out a framework to organize relevant variables
identified in theories and empirical research, iso-
lated knowledge acquired from studies of diverse
resource systems in different countries by bio-
physical and social scientists is not likely to
cumulate.

A framework is thus useful in providing a
common set of potentially relevant variables and
their subcomponents to use in the design of data
collection instruments, the conduct of fieldwork,
and the analysis of findings about the sustain-
bility of complex SESSs. It helps identify factors
that may affect the likelihood of particular policies
enhancing sustainability in one type and size of
resource system and not in others. Table 1 lists
the second-level variables identified in many em-
pirical studies as affecting interactions and out-
comes. The choice of relevant second or deeper
levels of variables for analysis (from the large set
of variables at multiple levels) depends on the
particular questions under study, the type of SES,
and the spatial and temporal scales of analysis.
To illustrate one use of the SES framework, I
will focus on the question: When will the users of
a resource invest time and energy to avert “a
tragedy of the commons”? Garrett Hardin (17)
earlier argued that users were trapped in accel-
erated overuse and would never invest time and
energy to extract themselves. If that answer were
supported by research, the SES framework
would not be needed to analyze this question.
Extensive empirical studies by scholars in diverse
disciplines have found that the users of many (but
not all) resources have invested in designing and
implementing costly governance systems to increase
the likelihood of sustaining them (3, 6, 7, 18).
A theoretical answer to this question is that
when expected benefits of managing a resource
exceed the perceived costs of investing in better
rules and norms for most users and their leaders,
the probability of users’ self-organizing is high
(supporting online material text). Although joint
benefits may be created, self-organizing to sustain
a resource costs time, and effort can result in a loss
of short-term economic gains. These costs, as well
as the fear that some users will cheat on rules
related to when, where, and how to harvest, can
lead users to avoid costly changes and continue to
overharvest (6). Accurate and reliable measures of
users’ perceived benefits and costs are difficult and
costly to obtain, making it hard to test theories
based on users’ expected net benefits.
Multiple variables that have been observed
and measured by field researchers are posited to
affect the likelihood of users’ engaging in collec-
tive action to self-organize. Ten second-level var-
iables (indicated by asterisks in Table 1) are
frequently identified as positively or negatively
affecting the likelihood of users’ self-organizing
to manage a resource (3, 6, 19, 20). To explain
why these variables are potentially important for
understanding sustainability and, in particular,
for addressing the question of when self-organization
activities will occur, I briefly discuss how they
affect perceived benefits and costs.
Size of resource system (RS). For land-related
resource systems, such as forests, very large ter-
ritories are unlikely to be self-organized given the
high costs of defining boundaries (e.g., surround-
ing with markers or fences), monitoring use pat-
terns, and gaining ecological knowledge. Very
small territories do not generate substantial flows
of valuable products. Thus, moderate territorial
size is most conducive to self-organization (15).
Fishers who consistently harvest from moder-
ately sized coastal zones, lakes, or rivers are also
more likely to organize (13) than fishers who
travel the ocean in search of valuable fish (5).
Productivity of system (RS5). A resource sys-
tem’s current productivity has a curvilinear effect
on self-organization across all sectors. If a water
source or a fishery is already exhausted or appar-
ently very abundant, users will not see a need to
manage for the future. Users need to observe some

Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.
Predictability of system dynamics (RS7). System dynamics need to be sufficiently predictable that users can estimate what would happen if they were to establish particular harvesting rules or new entry territories. Forests tend to be more predictable than water systems. Some fishery systems approach mathematical chaos and are particularly challenging for users or government officials (21).

Unpredictability at a small scale may lead users of pastoral systems to organize at larger scales to increase overall predictability (22, 23).

Resource unit mobility (RU1). Due to the costs of observing and managing a system, self-organization is less likely with mobile resource units, such as wildlife or water in an unregulated river, than with stationary units such as trees and plants in a lake (24).

Number of users (U1). The impact of group size on the transaction costs of self-organizing tends to be negative given the higher costs of getting users together and agreeing on changes (19, 20). If the tasks of managing a resource, however, such as monitoring extensive communal forests in India, are very costly, larger groups are more able to mobilize necessary labor and other resources (25). Thus, group size is always relevant, but its effect on self-organization depends on other SES variables and the types of management tasks envisioned.

Leadership (U5). When some users of any type of resource system have entrepreneurial skills and are respected as local leaders as a result of prior organization for other purposes, self-organization is more likely (19, 20). The presence of college graduates and influential elders, for example, had a strong positive effect on the establishment of irrigation organization in a stratified sample of 48 irrigation systems in Karnataka and Rajasthan, India (16).

Table 1. Examples of second-level variables under first-level core subsystems (S, RS, GS, RU, U, I, O and ECO) in a framework for analyzing social-ecological systems. The framework does not list variables in an order of importance, because their importance varies in different studies. [Adapted from (22)]

<table>
<thead>
<tr>
<th>Resource systems (RS)</th>
<th>Governance systems (GS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1 Sector (e.g., water, forests, pasture, fish)</td>
<td>GS1 Government organizations</td>
</tr>
<tr>
<td>RS2 Clarity of system boundaries</td>
<td>GS2 Non-government organizations</td>
</tr>
<tr>
<td>RS3 Size of system component*</td>
<td>GS3 Network structure</td>
</tr>
<tr>
<td>RS4 Human-construction facilities</td>
<td>GS4 Property rights systems</td>
</tr>
<tr>
<td>RS5 Productivity of system*</td>
<td>GS5 Operational rules</td>
</tr>
<tr>
<td>RS6 Equilibrium properties</td>
<td>GS6 Collective-choice rules*</td>
</tr>
<tr>
<td>RS7 Predictability of system dynamics*</td>
<td>GS7 Constitutional rules</td>
</tr>
<tr>
<td>RS8 Storage characteristics</td>
<td>GS8 Monitoring and sanctioning processes</td>
</tr>
<tr>
<td>RS9 Location</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource units (RU)</th>
<th>Users (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RU1 Resource unit mobility*</td>
<td>U1 Number of users*</td>
</tr>
<tr>
<td>RU2 Growth or replacement rate</td>
<td>U2 Socioeconomic attributes of users</td>
</tr>
<tr>
<td>RU3 Interaction among resource units</td>
<td>U3 History of use</td>
</tr>
<tr>
<td>RU4 Economic value</td>
<td>U4 Reputation</td>
</tr>
<tr>
<td>RU5 Number of units</td>
<td>U5 Leadership/entrepreneurship*</td>
</tr>
<tr>
<td>RU6 Distinctive markings</td>
<td>U6 Norms/social capital*</td>
</tr>
<tr>
<td>RU7 Spatial and temporal distribution</td>
<td>U7 Knowledge of SES/mental models*</td>
</tr>
<tr>
<td>RU8 Networking activities</td>
<td>U8 Importance of resource*</td>
</tr>
<tr>
<td>RU9 Location</td>
<td>U9 Technology used</td>
</tr>
</tbody>
</table>

Interactions (I) → outcomes (O)

<table>
<thead>
<tr>
<th>Interactions (I) → outcomes (O)</th>
<th>Users (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1 Harvesting levels of diverse users</td>
<td>O1 Social performance measures (e.g., efficiency, equity, accountability, sustainability)</td>
</tr>
<tr>
<td>I2 Information sharing among users</td>
<td>O2 Ecological performance measures (e.g., overharvested, resilience, bio-diversity, sustainability)</td>
</tr>
<tr>
<td>I3 Deliberation processes</td>
<td>O3 Externalities to other SESs</td>
</tr>
<tr>
<td>I4 Conflicts among users</td>
<td></td>
</tr>
<tr>
<td>I5 Investment activities</td>
<td></td>
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<td>I6 Lobbying activities</td>
<td></td>
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<tr>
<td>I7 Self-organizing activities</td>
<td></td>
</tr>
<tr>
<td>I8 Networking activities</td>
<td></td>
</tr>
</tbody>
</table>

Related ecosystems (ECO)

ECO1 Climate patterns. ECO2 Pollution patterns. ECO3 Flows into and out of focal SES.

*Subset of variables found to be associated with self-organization.
remedy this initial failure, the government re-
opened the fishery but divided the coastal area
into more than 50 sectors, assigned transferrable
quotas, and required that all ships have neutral
observers onboard to record all catches (32).
Furthermore, the long-term sustainability of
rules devised at a focal SES level depends on
monitoring and enforcement as well as their not
being overruled by larger government policies. The
long-term effectiveness of rules has been shown
in recent studies of forests in multiple countries to
depend on users’ willingness to monitor one an-
other’s harvesting practices (15, 31, 33, 34). Larger-
scale governance systems may either facilitate
or destroy governance systems at a focal SES level.
The colonial powers in Africa, Asia, and Latin
America, for example, did not recognize local
resource institutions that had been developed
over centuries and imposed their own rules, which
frequently led to overuse if not destruction (3, 7, 23).

Perspective

Economic Networks:
The New Challenges

Frank Schweitzer,*,1 Giorgio Fagiolo,2 Didier Sornette,1,3 Fernando Vega-Redondo,4,5 Alessandro Vespignani,3,6 Douglas R. White6

The current economic crisis illustrates a critical need for new and fundamental understanding of the structure and dynamics of economic networks. Economic systems are increasingly built on interdependencies, implemented through trans-national credit and investment networks, trade relations, or supply chains that have proven difficult to predict and control. We need, therefore, an approach that stresses the systemic complexity of economic networks and that can be used to revise and extend established paradigms in economic theory. This will facilitate the design of policies that reduce conflicts between individual interests and global efficiency, as well as reduce the risk of global failure by making economic networks more robust.

The economy, as any other complex sys-
tem, reflects a dynamic interaction of a large number of different agents, not just a few key players. The resulting systemic be-
havior, observable on the aggregate level, often shows consequences that are hard to predict, as illustrated by the current crisis, which cannot be simply explained by the failure of a few major agents. Thus, we need a more fundamental in-
sight into the system’s dynamics and how they
can be traced back to the structural properties of the underlying interaction network.

Research examining economic networks has been studied from two perspectives; one view comes from economics and sociology; the other originated in research on complex systems in physics and computer science. In both, nodes represent the different individual agents, which can represent firms, banks, or even countries, and where links between the nodes represent their mutual interactions, be it trade, ownership, R&D alliances, or credit-debt relationships. Different agents may have different behaviors under the same conditions and have strategic interactions (1). These evolving interactions can be represented by network dynamics that are bound in space and time and can change with the environment and coevolve with the agents (2). Networks are formed or devolve on the basis of the addition or deletion of either agents or the links between them.

The socioeconomic perspective has empha-
sized understanding how the strategic behavior of the interacting agents is influenced by—and reciprocally shapes—relatively simple network architectures. One common example is that of a star-spoke network, like a very centralized or

References and Notes
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