SUSTAINABILITY

Prediction, precaution, and policy under global change

Emphasize robustness, monitoring, and flexibility

By **Daniel E. Schindler*** *and* **Ray Hilborn**

A great deal of research to inform environmental conservation and management takes a predict-and-prescribe strategy in which improving forecasts about future states of ecosystems is the primary goal. But sufficiently thorough understanding of ecosystems needed to reduce deep uncertainties is probably not achievable, seriously limiting the potential effectiveness of the predict-and-prescribe approach. Instead, research should integrate more closely with policy development to identify the range of alternative plausible futures and develop strategies that are robust across these scenarios and responsive to unpredictable ecosystem dynamics.

Calls for improving forecasts of future ecosystem states are common [e.g., (*1*)]. It is often assumed that poor performance of forecasting models (*2*) derives from weak understanding of ecological complexity and that developing richer mechanistic appreciation of ecological interactions will improve forecasts (*3*). There is also belief that statistical down-scaling of global climate models will improve the accuracy of coupled climate-ecosystem models [e.g., (*4*)]. The utility of this information for improving forecasts of ecosystems is likely small; it is most useful for explaining observed ecological dynamics post hoc. The primary values of ecosystem models are as heuristic tools for communication and for developing scenarios to express uncertainties and test policies; reliable forecasts will remain elusive.

POLICY

Scenario planning is used in many disciplines to assist policy development in situations with deep and irreducible uncertainties (*5*–*7*). A range of information sources, which can include models, is used to develop alternative plausible trajectories of ecosystems; uncertainties about the future are represented by the range of conditions captured by the ensemble of scenarios. In contrast, forecasts narrowly limit uncertainties to those associated with a single potential outcome that is assumed to be predictable; policy developed under this premise will prepare us poorly for the unpredictable (*7*).

LIMITS OF MODELS. Ecosystems are organized around a seemingly infinite number of biological, chemical, and physical processes that play out across enormous ranges of space and time scales (*8*). Feedback mechanisms provide stability such that ecosystems appear stable during some time frames but can abruptly shift to express new structures in others (*9*). Our abilities to make observations are limited to a small range of space and time scales (*8*), limiting our capacity for understanding ecosystems and forecasting how they will respond to local and global change. Thus, environmental management will always operate in a realm where uncertainties dominate (*10*). Although more detailed knowledge about ecological processes will certainly be produced, reliable forecasts will likely accumulate much slower than will be useful for contributing to effective policy for sustainability or conservation, and ecosystems will likely change faster than knowledge accumulates.

PHOTO: KHLONGWANGCHAO/THINKSTOCK

A wide range of modeling approaches is used to explore and forecast ecosystem dynamics. However, models are prone to errors that can mislead policy if not treated with appropriate skepticism (*11*). For example, in statistical models, historical time series are often compared to quantify cause-and-effect relationships between resources and environmental variables. Without controlled manipulations and appropriate reference systems, such comparisons can lead to false conclusions, based on spurious correlations, about cause-and-effect relationships. For example, a reanalysis of 47 previously published relationships between environmental variation and recruitment in marine fish—after including an additional decade of new data—revealed that only one of the previous statistically determined relationships was still used in management because the initial correlations failed to persist through time (*12*).

Nonstationarity in ecosystem relationships (i.e., evolution of parameters that quantify them) adds substantial uncertainty to models, even if statistical relationships are based on real interactions in ecosystems. For example, changing climate and land-use are fundamentally changing the statistical relationships (e.g., between precipitation and river flow) that provide the foundation for water resource planning (*13*). Retrospective analyses of relationships between interacting variables are often used as the basis for forecasting tools. However, in ecological models, statistical parsimony often selects retrospective models that have more mechanistic detail than can be supported when evaluating their forecast performance; the best forecast models are typically mechanism-free, relying on emergent statistical properties of data to make short-term projections (*2*, *14*).

It is typical to validate or verify a numerical model by assessing its ability to accurately simulate observed changes in an ecosystem. However, in even modestly complicated models, simulations can recapture observed dynamics, but for entirely wrong mechanistic reasons (*11*, *15*). Thus, current approaches to verification and validation of ecosystem models likely produce overly optimistic impressions of the reliability of forecasts underlying management and conservation prescriptions.

School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA.
**E-mail: deschind@uw.edu*

Published by AAAS

ROBUST, FLEXIBLE, MONITORED. Instead of hoping that revealing mechanistic details of ecosystems will provide solutions for achieving sustainability, we summarize the following general principles for developing effective environmental policy.

Policy robustness. In development of environmental policy and the science to support it, emphasis should be placed on assessing robustness: the ability of policies to perform well despite scientific uncertainty (*6*). Risk management through strategies like hedging is an obvious component of this. For example, analysis of freshwater wetlands suggests that a risk dispersion approach to maintaining habitat networks will look substantially different than prescriptions that emerge from assuming causal relationships are known and stationary (*16*). In this case, climate and habitat models can be used to develop scenarios that capture uncertainties in our knowledge of climate effects.

Heterogeneity and options. Effective policy should pursue mechanisms for developing resilience to risks associated with unknowable future changes in ecosystems. Management that maintains ecosystem heterogeneity may improve the reliability of important resource flows [e.g., (*17*)] because response diversity increases the probability that some components will maintain ecological functions under new environmental conditions. Strategic investment in networks of current and possible future habitats under different climate and land-use scenarios does not necessarily require precise forecasts about future climate conditions or effects (*18*). Policies that maintain options for habitats, organisms, and genes will likely be least sensitive to uncertain future risks.

Monitoring and assessment. More emphasis needs to be placed on high-quality monitoring and assessment of ecosystems (*19*). Monitoring must be tailored to address specific questions about ecosystem conditions, and rigorous assessment of data within the context of prevailing theory needs to be routine to evaluate ecological responses to management.

As budgets for science and management shrink, there is a tendency to scale back on investments in monitoring and assessment [e.g., (*20*)] and switch funding to support mechanistic science and predictive modeling. This is a mistake. Although generally not considered as intellectually rich as mechanistic science, accurate assessments of resource states and ecosystem services must be given high priority (*19*). Without monitoring and assessment, we have no way to determine when changes to management are needed (*21*).

> ***"the best forecast models are typically mechanism-free, relying on emergent statistical properties of data to make short-term projections ..."***

Management flexibility and responsiveness. The precautionary approach is widely invoked in situations with deep uncertainty in cause-and-effect relationships and in estimating environmental damage from human activities. The typical application of precautionary management is to limit human activities to within a range over which acceptable levels of damage have been observed. This "better safe than sorry" approach may have unintended consequences that make it a weak strategy. First, there is little opportunity to learn when managing solely within the range of past variation; active probing is usually needed to determine how ecosystems respond to perturbations (*21*). Second, slow response times in ecosystem processes may give the false impression that an ecosystem is unresponsive to specific perturbations until the system is sufficiently degraded that it is difficult to restore (*9*). Third, we should expect that the future is not likely to be a simple extrapolation of the recent past. We should ask (i) what are we doing to detect and quantify shifts to new ecosystem states (*22*) and (ii) what could management regimes do if we were to arrive in these new conditions?

Policy should embrace a different dimension of precaution: flexibility. The ability to adapt to ecosystem changes revealed by monitoring and assessment is likely to be a far more powerful strategy than assuming that what has worked in the past will work in the future. Research is needed to establish benchmarks for assessing potential policy performance at the development phase, not after it is apparent that a given policy is failing. The best management and conservation plans will likely be those that can harness unexpected opportunities, while having strategies to adapt when the system moves to undesirable states. A critical step in developing flexible policies is identifying reliable metrics of ecosystem condition to which policy strategies can adjust (*6*). Planning efforts should consider the costs to future actions of any specific policy; those that will be costly to reverse should be discounted.

Such policy flexibility would have been useful in sustaining fishing communities in eastern Canada after changing climate and overfishing caused economic extinction of the Atlantic cod fishery. Freed of predation from cod, production of shellfish and crustaceans more than compensated for economic losses due to closure of cod fisheries (*23*). However, due to rigid regulation of fishing permits (people who had not harvested shellfish in recent years did not hold shellfish permits), families that depended on cod were out of work, replaced by an entirely different sector that harvested shellfish and crustaceans. Had policy enabled fishers to switch among the species they harvested as populations waxed and waned, there might have been less pressure to continue exploiting cod, and the social meltdown that cost Canadians billions of dollars might have been avoided. Policies that lock fishers into specific species and gears are not robust to changes in abundance or species composition of marine ecosystems. Policies that allocate fishing rights across a range of species to communities rather than individuals are likely to be more robust (*24*, *25*).

Resource management and conservation will always involve substantial trial and error, despite huge efforts in basic science to reduce and understand uncertainties. The best we can likely do is enable our abilities to change course as new limits to ecosystems or new opportunities are discovered. ■

REFERENCES AND NOTES

1. J. S. Clark *et al*., *Science* **293**, 657 (2001).
2. E. J. Ward, E. E. Holmes, J. T. Thorson, B. Collen, *Oikos* **123**, 652 (2014).
3. J. Travis *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **111**, 581 (2014).
4. J. Franklin *et al*., *Glob. Change Biol.* **19**, 473 (2013).
5. P. J. H. Schoemaker, *Sloan Manage. Rev.* **36**, 25 (1995).
6. R. J. Lempert, M. E. Schlesinger, *Clim. Change* **45**, 387 (2000).
7. G. D. Peterson, G. S. Cumming, S. R. Carpenter, *Conserv. Biol.* **17**, 358 (2003).
8. S. A. Levin, *Ecology* **73**, 1943 (1992).
9. C. S. Holling, *Ecosystems* **4**, 390 (2001).
10. D. Ludwig, R. Hilborn, C. Walters, *Science* **260**, 17 (1993).
11. J. T. Schnute, L. J. Richards, *Can. J. Fish. Aquat. Sci.* **58**, 10 (2001).
12. R. A. Myers, *Rev. Fish Biol. Fish.* **8**, 285 (1998).
13. P. C. Milly *et al*., *Science* **319**, 573 (2008).
14. C. T. Perretti, S. B. Munch, G. Sugihara, *Proc. Natl. Acad. Sci. U.S.A.* **110**, 5253 (2013).
15. N. Oreskes, K. Shrader-Frechette, K. Belitz, *Science* **263**, 641 (1994).
16. A. W. Ando, M. L. Mallory, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 6484 (2012).
17. D. E. Schindler *et al*., *Nature* **465**, 609 (2010).
18. J. Lawler *et al*., *Front. Ecol. Environ* **8**, 35 (2010).
19. G. M. Lovett *et al*., *Front. Ecol. Environ* **5**, 253 (2007).
20. C. Lorenz, H. Kunstmann, *J. Hydrometeorol.* **13**, 1397 (2012).
21. C. Walters, *Adaptive Management of Renewable Resources* (MacMillan, New York, (1986)
22. M. Scheffer *et al*., *Science* **338**, 344 (2012).
23. R. Hilborn, A. E. Punt, J. Orensanz, *Bull. Mar. Sci.* **74**, 493 (2004).
24. M. Makino, H. Matsuda, *Mar. Policy* **29**, 441 (2005).
25. J. C. Castilla, O. Defeo, *Rev. Fish Biol. Fish.* **11**, 1 (2001).

ACKNOWLEDGMENTS

We thank the U.S. National Science Foundation–Dynamics of Coupled Natural and Human Systems Program, and the Harriet Bullitt Professorship for funding.

10.1126/science.1261824