Ecological forecasts: an emerging imperative

James S. Clark,[1*] Steve Carpenter,[2] Mary Barber,[3] Scott Collins,[4] Andy Dobson,[5] Jon Foley,[6] David Lodge,[7] Mercedes Pascual,[8] Roger Pielke, Jr,[9] William Pizer,[10] Cathy Pringle,[11] Walt Reid,[12] Kenny Rose,[13] Osvaldo Sala,[14] William Schlesinger,[15] Diana Wall,[16] David Wear[17]

[1]Department of Biology, Duke University, Durham, NC 27708 USA.

[2]University of Wisconsin Center for Limnology, Madison WI 53706 USA

[3]Ecological Society of America, 1707 H St, NW, Suite 400, Washington, DC 20006

[4]National Science Foundation, 4201 Wilson Boulevard, Arlington, Virginia 22230, USA

[5]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544, USA

[6]Atmospheric & Oceanic Sciences, University of Wisconsin, Madison WI 53706 USA

[7]Department of Biology, University of Notre Dame, Notre Dame, Indiana 46556 USA

[8]Department of Biology, University of Michigan, Ann Arbor, MI 48109 USA

[9]ESIG/NCAR, 3250 Mitchell Lane, Boulder, CO 80301, USA

[10]Resources for the Future, 1616 P Street NW Washington, DC 20036 USA

[11]Ecology, University of Georgia, Athens, GA USA

[12]World Resources Institute, 10 G Street, NE (Suite 800), Washington, DC 20002 USA

[13]Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, Louisiana 70803 USA

[14]Department of Ecology, University of Buenos Aires, Buenos Aires 1417, Argentina

[15]Nicholas School of Environment and Earth Sciences, Duke University, Durham NC 27708 USA

[16]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80523, USA

[17]USDA Forest Service, PO Box 12254, Research Triangle Park, NC 27709, USA

*to whom correspondence should be addressed. Email: jimclark@duke.edu

Planning and decision making can be improved by access to reliable forecasts of ecosystem state, ecosystem services, and natural capital. Emerging computing capacity together with broad-scale studies of ecosystem effects will soon make it possible to predict many aspects of environmental change. An agenda that would lead toward a capacity to produce, evaluate, and communicate forecasts of critical

ecosystem services requires a process that engages scientists and decision makers. Interdisciplinary linkages are necessary in view of the climate and societal controls on ecosystem services, the feedbacks involving social change, and the decision making relevance of forecasts.

A 1981 report predicting that the Eurasian zebra mussel (*Dreissena polymorpha*) would become established in the Laurentian Great Lakes gained the attention of neither policy makers nor the general public. Five years later, zebra mussels were discovered in Lake St. Clair, and they soon spread to all Great Lakes, the Mississippi River, and most of the lakes and rivers of the upper Midwest. In the Great Lakes basin alone annual mitigation costs to industry from $20 to $100 million will continue into the foreseeable future. Unquantified, noncommercial costs include losses of biodiversity, such as the extirpation of native clams (Strayer 1999), and shifts in ecosystem energy flows and productivity. No regulatory actions can be traced to the 1981 document predicting the invasion. The invasion itself prompted a flurry of reactive legislative acts, culminating in the Aquatic Nuisance Species Act of 1990-91, which instituted voluntary guidelines to reduce the likelihood of future introductions from ship ballast.

The zebra mussel experience highlights issues concerning the state of environmental science and its place in planning for global change. This forecasting “success” is unrepresentative of the generally poor record of predicting the spread of exotic aliens. Anticipating many of the environmental challenges of coming decades requires improved scientific understanding. An evolving science of ecological forecasting is beginning to emerge and could have an expanding role in policy and management.

Any satisfaction ecologists might gain from an “accurate” forecast is overshadowed by apparent failure to affect the outcome. Scientists and policy makers can agree that success in dealing with environmental change rests with a capacity to anticipate the consequences of purposive actions. Rapid change in climate and chemical cycles, depletion of the natural resources that support regional economies, proliferation of exotic species, spread of disease, and deterioration of air, waters, and soils pose unprecedented threats to human civilization. Continued food, fiber, and freshwater supplies and maintenance of human health depend on our ability to anticipate and prepare for the uncertain future. In 1981, the science was capable of anticipating an invasion and of recognizing its importance. But this scientific foresight did not translate to proactive practices that might have preempted an environmental and economic disaster.   In this case the science was ready, but there was no effective process for informing decision makers.

An initiative in Ecological Forecasting must define the appropriate role of science in the decision making process and the new science that is required to develop the capability. *Ecological forecasting* is defined here as the process of predicting the state of ecosystems, ecosystem services, and natural capital, with fully specified uncertainties, and contingent on explicit scenarios for climate, land use, human population, technologies, and economic activity. The spatial extent ranges from small plots of land to regions to continents to the globe. The time horizon of forecasts can extend 10 to 50 years. The *information* content of a forecast[1] is inversely proportional to forecast uncertainty. A wide confidence envelope indicates low information content. A *scenario* assumes changes in “a limited set of possible future boundary conditions (e.g., emissions scenarios) … For, the decision maker, scenarios provide an indication of possibilities, but not definitive probabilities” (MacCracken http://www.esig.ucar.edu/socasp/zine/26/guest.html). Scenarios can be the basis for *projections*, which apply the tools of ecological forecasting to specific scenarios.

Here we examine the need for and promise of an initiative in Ecological Forecasting. We begin by summarizing valued ecosystem services in the context of our need to anticipate change. We follow with perspectives on two themes that could determine the effectiveness of ecological forecasting for decision making. First is the need for interaction with the social sciences in order to enhance usefulness to decision makers and the general public. The second theme concerns the science that is needed to provide skillful, timely, and relevant ecological forecasts, including data adequacy and strategies for model development, implementation, and evaluation. Distinctions involving models for decision making versus advancing scientific understanding, scenarios versus forecasts, and extensions to the decision process are part of the broad agenda.

Where is forecasting needed?

Freshwater ecosystems

Humans have appropriated half of the accessible global freshwater runoff, and this could climb to 70% by the year 2025 (Postel et al. 1996). Nearly 2/3 of all rivers are regulated in some manner (Abramovitz 1996), causing fragmentation, deterioration, and losses of floodplains, wetlands, and riparian ecosystems (Pringle, in press). Irrigation has dramatically reduced water levels in major closed basins (*e.g. Aral Sea, Lake Chad*) and the discharge of river systems (*e.g.* the *Colorado, Nile, Ganges, Amu Darya,* and *Syr Darya*). In recent decades more than 20% of the known 10,000 freshwater fish species have become threatened, endangered, or extinct (WRI 2000). Forty percent of the human population occupies river basins that experience water scarcity; by 2050, this number will increase to 50%. With the exception of agencies in developed countries responsible for forecasting floods that might threaten life or property, there is no mechanism to warn of changes in freshwater ecosystems and how to respond to them.

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[1] Adapted from the notion of (generalized) Fisher Information (as opposed to the Information Theory

Providing ecological forecasts of the consequences of hydrologic change, pollution, and effects of exotic species on freshwater ecosystems represents a broad scientific challenge (e.g., Postel and Carpenter 1997, Postel 1999, Naiman et al. 2000, NAS 2000, Pringle in press).

Food Supply

By 2050, a burgeoning human population will depend on agricultural science to prevent widespread shortfalls in food supply. Past reliance on intensive land use, high-yielding crops, industrially produced fertilizers and pesticides, irrigation, and mechanization comes with environmental costs that can include damage to soil structure and contamination of water and food products (Wagstaff 1987, Tilman et al. 2000). Devastating consequences can result from failure to consider agricultural practice in the context of regional ecosystem function. During Hurricane Floyd, waste from factory–sized hog farms enriched streams and affected human health and the function of coastal estuaries.

Environmental and financial concerns are beginning to motivate less intensive agricultural systems (*e.g.*, Dalgaard *et al.* 1998; Halberg and Kristensen, 1997; DARCOF, 1999) that require an understanding of interactions involving agriculture and basic ecosystem services, including supply of clean air and water, maintenance of soil fertility, nitrate leaching, and pollination. Forecasting the impacts of agriculture under developing agromanagement systems requires a broad examination of tillage practices, fertilizer use, crop rotations, and irrigation strategies in the context of local and regional ecosystem function. At present there is no integrated strategy for anticipating these interactions and their consequences for global food supply.

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definition as the log-likelihood ratio)

The Carbon Cycle

The continuing rise of CO_2 in Earth's atmosphere, and its potential to cause significant climate changes, demands two levels of ecological forecasting. The first level concerns the effects of higher CO_2 and temperature on plant growth, water use, and pest resistance, and how these responses will differ among species. Forecasts would have immediate relevance for farmers and foresters, who stand to lose economically if the wrong crops or trees are planted. Differential growth and competitive ability of species in response to rising CO_2 will determine how diversity, structure, and function may respond to changing CO_2 and climate. Public health officials could benefit from ecological forecasts of flowering phenology, pollen production, and severity of pollen allergens in the environment.

A second level of ecological forecast stems from the impact of plants on the rise of atmospheric CO_2, mediated by biosphere storage (or loss) of carbon, a key ecosystem service. Knowledge of biomass, net primary production, and soil carbon storage can be used to anticipate future ecosystem function and diversity in the face of climate change. These predictions have economic significance: for instance, the Kyoto protocol includes provisions for emissions trading. A country that sees net carbon storage in its vegetation and soils could sell that quantity as a "credit" to a country that is unable to curb its fossil fuel emissions. Accurate assessments of the carbon sequestration will be valuable to the emerging business of "emissions trading." The interactions involving CO2, climate, nutrients, and plant physiology are not yet sufficiently understood to permit informative forecasts of carbon storage.

Living resources

Extinctions, invasions, and habitat loss impact ecosystem function (e.g., nutrient cycling, fire, primary productivity) and the capacity of ecosystems to supply critical goods and services. Diversity and habitat loss affect ecosystem variability and resilience to perturbations. Some of these effects can be immediate, whereas others are not apparent for decades. For example, salmon extinction has attenuated nutrient supply to Pacific Northwest rivers, with consequent, slow change in community composition and structure (Naiman et al. 2000). Introduced cheatgrass in the western United States has altered composition, nutrient cycles, and disturbance regimes (Mack et al. 2000). The value of biodiversity extends beyond these rather direct goods and services. Nations around the world have invested in parks and protected areas, not only because there is economic value in tourism, but also because the public values biodiversity.

There is broad demand for biodiversity forecasts. Conservation biologists require predictions of extinction risk that are more accurate than simple species-area curves applied to habitat loss (MacArthur & Wilson 1967, Reid 1992, Brooks *et al*. 1997, Pimm *et al*. 1995, Harte & Kinzig 1997, Harte *et al*. 1999, Seabloom *et al*. in review). For example, habitat loss does not lead to complete diversity loss outside of the remaining habitat island; some species persist, even flourish, in converted lands and at edges. Spatial aspects of extinction risk have conservation relevance (Doak *et al*. 1992, Doak 1995). There is need to anticipate spread and impact of nonindigenous species (NIS) on ecosystem function, food supplies, commerce, and recreation (Lodge 1993, Sala et al 2000). Introductions can be irreversible, and mitigation is difficult and expensive. Biodiversity prediction could have immediate impact on policy related to food supply, freshwater, and human health, it would publicize the biodiversity crisis of mass extinction, and it could inform preventative or mitigative actions against introduction and spread of NIS.

Disease

The recent outbreak of foot and mouth disease in the United Kingdom emphasizes the importance and potential of ecological forecasting. The disease appeared on a farm in northern England in February 2001. Within two weeks it was reported from at least 10 other locations in England. Over three million livestock have been slaughtered at a cost of $5.2 billion to Britain's farmers (Economist, May 5th, 2001, p49).

Scenarios for the course of the foot and mouth epidemic (Anderson et al 2001) proved remarkably accurate, but interactions involving ecological and socioeconomic factors typically make disease forecasting difficult (Schmidt and Ostfeld 2001, Dobson & Foufopoulos, 2001, in press). Cholera dynamics depend on climate variability (Franco et al. 1997; Colwell, 1996; Pascual et al., 2000) and socioeconomic interactions (Bonilla-Castro et al., 2000). Measles epidemiology is most accurately predicted at the national level and within large cities. It is harder to predict at intermediate scales, where movements of infectious individuals depend on connectance of population centers.

Despite the complexity, forecasts and model scenarios have already provided invaluable guidance for prevention measures, the design of vaccination programs, and drug-use strategies. In the case of foot and mouth disease, scenarios for several potential interventions were the basis for the decision to escalate slaughter of infected herds. In general, preventive measures are critical when vaccines are not yet an effective option, especially in light of growing resistance to drugs and the breakdown of public health in large regions of the globe. Drug resistance is unlikely to be solved by the development of new drugs. Epidemiological models should continue to play a role with the evolution of new and resistant strains (Levin et al 1999).

Ecological forecasting goals and challenges

The foregoing themes face common challenges that fall within the goals of an initiative to anticipate change. Technical construction of forecasts requires initiatives to develop new or augment existing data networks, to support experimental research, to develop modeling approaches.

Data from experiments and monitoring networks

Experimental and observational data at coarse scales are a foundation for forecasting capability. Large experiments are critical, because landscape processes are often unpredictable from fine-grained studies (Carpenter 1996, Clark et al. 1999). The feedbacks from vegetation to climate become important only when the spatial extent of a study rises above a critical threshold. Factorial, whole-ecosystem experiments with manipulations of CO_2, temperature, moisture, nutrients, and species may be the only way to determine interactions that control forest responses to global change. For example, Free-Air CO2 Enrichment studies (FACE) show that the water stress expected from studies of individual plants are not realized when stands of forest trees are subjected to elevated CO_2 (Ellsworth 2000).

Data networks can provide a baseline for forecasting models. Missing variables, poor resolution, inadequate duration, temporal and spatial gaps, and declining coverage are pervasive limitations. Due to abandonment of precipitation, stream-height, and discharge gauges (IAHS 1999), the capacity to forecast droughts and floods was greater 30 years ago than it is today. Countries with the poorest hydrological networks (e.g., sub-Saharan Africa, arid regions of the former Soviet Union) have the most pressing water needs (Stokstad 1999). The problem is not restricted to developing and transitional economies. There is an average density of one stream gauge per 1024 km^2 in the lower 48 states of the US (Brabets 1996). Since 1971 there has been a 22% decline in gauging stations that record flow on small US rivers (Stokstad 1999). Sustained monitoring is needed that can dovetail with forecasts in an adaptive feedback design.

The ability to anticipate exotic invasions would benefit from historic records of species introductions and their vectors (e.g., ship traffic). Where eventual colonization seems inevitable (e.g., zebra mussels in the Midwestern United States) forecasts may guide mitigative actions. Disease forecasting can likewise require extensive spatial and temporal data, such as those used to inform intervention for foot and mouth disease. Prediction of childhood epidemics depends on host population growth rate and age-specific mixing patterns. Long records of births and vaccinations can permit predictions of cycles, including those that are regionally synchronized and spatially incoherent (e.g. Finkestadt and Grenfell 2000, Earn et al. 2000). Cholera and malaria predictions require climate data, which determine spread of pathogens and vectors.

Developing technologies do not fully compensate for sparse data, but they promise to facilitate forecasting in other ways. In the case of hydrologic forecasting, remote sensing, together with geophysical tomography, can provide high-resolution coverage of precipitation and the effects of dams and irrigation (NAS 2000). Biogeochemical cycles, hydrology, and biodiversity forecasts require land inventory and census data (Richards 1990) combined with satellite-based data (Ramankutty & Foley, 1998, 1999). Satellites could be used to monitor habitat loss, a predictor of extinction risk.

Satellite data could inform global scenarios for disease spread in response to environmental degradation and climate change (Michael et al. 1999). Prevalence of hantavirus pulmonary syndrome (HPS), a viral disease characterized by acute respiratory distress with a high death rate (Glass, 2000) depends on infection rates of its host, the common deer mouse (*Peromyscus maniculatus*). The 1993 HPS outbreak in the U.S. Southwest was attributed to unusual weather of 1991-92 that was quantified from Landsat Thematic Mapper satellite imagery. A model developed for the 1993 outbreak that followed an El Nin~o year provided accurate predictions for the 1995 non-El Nin~o year. Surveillance networks could likewise improve understanding of climate constraints on malaria and its vectors (Dye and Reiter, 2000; Rogers and Randolph 2000) and of the extreme climate events that forewarn of cholera risk (Pascual et al. 2000).

In summary, models needed to develop forecasts and to explore scenarios of change depend on experimental and observational data at coarse scales. Implementation of new initiatives and maintenance of key existing ones are central to an Ecological Forecasting initiative.

Computational challenges

Forecasts are constructed with the aid of models that can involve variables and processes as diverse as the immigration of alien species, socioeconomic pressures on land use, communicable disease, and biosphere carbon sequestration. Computational challenges related to the rapid evaluation of spatial fields and disk access time require greater attention to algorithms and data structures than is typically practiced by ecologists[2]. Collaborations involving ecologists and computer scientists are essential.

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[2] New approaches, such as the fast multipole algorithm (Greengard 1988), have become a standard tool in celestial mechanics and molecular dynamics for spatiotemporal problems.

What is forecastable?

Accurate estimation and communication of reliability and information content will determine the success of an Ecological Forecasting initiative. “Forecastable” ecosystem attributes are ones for which uncertainty can be reduced to the point where a forecast reports a useful amount of information. Information content is affected by all sources of stochasticity. Low information content can result because drivers (and, thus, model structures) are uncertain, parameters are uncertain, and unknown human responses to ecosystem change (or even to forecasts of ecosystem change) affect outcomes. Many sources of stochasticity are typically ignored in ecological models. When reported at all, prediction uncertainties are typically confined to estimation error (e.g., Lande 1987, Pacala et al. 1996). Estimation error is reduced by sampling, and is often overwhelmed by other sources of uncertainty.

“Inherent” uncertainty that results from strong nonlinearities and stochasticity is most daunting, but it can still benefit from analysis. Inherent uncertainty will always prevent informative forecasts of spread velocity for many invasive organisms. Complete knowledge of parameters that might be estimated, for example, through detailed study of long distance dispersal, would do little to increase forecast information (Clark et al. 2001). But analysis shows that scientific efforts should be focussed on factors affecting invasion potential, such as the mechanisms of long-distance dispersal.

The inherent uncertainty involved in extinction risks leads ecologists to disagree on the value of predictions from population viability models (Brook *et al*. 2000). Extinction forecasts are highly sensitive to poorly constrained assumptions (Ludwig1999). Ecological models typically ignore the individual variability that plays a large role in population growth (and decline). New computational approaches represented by hierarchical models accommodate multiple stochastic elements (Carlin and Louis 2000) and can be used to accurately estimate and propagate uncertainty in population growth (Clark, in prep). Weather and climate models continue to develop new applications for these recent techniques (e.g., Wikle, in prep.), but they are not widely exploited in ecological models.

The capacity to forecast processes with large inherent uncertainty will further improve as ecologists identify the "slow" variables that forewarn of consequences years in advance. Whereas deterministic weather forecasts confront an approximate two-week limit, probabilistic climate prediction makes use of the system memory represented by sea-surface temperatures. The limitations imposed on a deterministic weather forecast by nonlinearities may not defeat efforts to provide informative climate forecasts (NRC 1999). There are many examples of "slow variables" that constrain ecological processes (Carpenter and Turner 2000). For example, successional change in forests is constrained by climate and soils. If these change slowly relative to tree lifespans, succession is predictable using physiology and competitive interactions among trees (Shugart 1984, Pacala et al. 1996). Land-use change is determined by individual decisions that are influenced by a variety of needs and goals. Yet decade-scale land-cover change can be predictable based on overriding controls imposed by topography and distance to market centers (Wear and Bolstad 1998).

Agricultural practices result from complex decisions, yet slow variables can be the basis for useful projections. Projections of subsidies to global food production (irrigation, fertilizers, and transport and storage of crops) (Tilman 2000) can inform forecasts of downstream eutrophication in coastal fisheries and increases in atmospheric greenhouse gases (CH_4,CO_2,N_2O) (Robertson et al. 2000). Ecologists can forecast how environmental change affects carbon storage in agriculture, production forestry, and natural ecosystems. N deposition leads to predictable changes in plant composition and reduced carbon storage potential in tallgrass prairie soils (Wedin and Tilman 1996). Knowledge of fertilizer and irrigation effects on carbon storage in agroecosystems can be used to forecast how managed ecosystems will contribute to or stem the future rise of CO_2 in Earth's atmosphere (Schlesinger 1999).

The developing capacity for prediction requires careful model evaluation and communication of forecast information. Model evaluation may involve model selection, model averaging, or both. Techniques for model evaluation developed in econometrics, finance, and meteorology can be used to evaluate ecological forecasts through hind casting (Judge et al. 1982) and their ability to identify turning points and events (Wear and Bolstad 1998).

Ecological forecasting will provide variable amounts of information on the ecosystem services that humans value. Failing to accommodate the dominant sources of variability makes for a forecast that contains less information than it purports (confidence intervals are misleadingly narrow). Inevitable forecast failures erode confidence (NRC 1999). Sources of uncertainty, their potential impacts on forecast information, and the identification of overriding controls that change slowly, must be considered when deciding where efforts can be of most value.

Decision making and the role of forecasts

A developing capacity for prediction has not yet been integrated as part of a comprehensive prediction process (Sarewitz et al. 2000). Missed opportunities to engage ecological understanding have become a source for growing concern. The zebra mussel experience illustrates that the $138 billion spent annually on control of NIS (Pimentel et al.

2000) can be blamed, in part, on failure to communicate science. Forecasts based solely on scientific objectives have little impact on policy (Sarewitz and Pielke 1999), because there is no stake-holder (NRC 1999). Priorities for ecological forecasting must come from dialog that insures active participation by policy makers, managers, and general public.

Some experience suggests that a proactive approach holds promise. Pesticide use has declined, in part, due to the Montreal Protocol, which was drafted in response to scenarios for ozone-depleting chemicals in the atmosphere. Policy makers can respond to research that is motivated by management or conservation interests. For example, population studies, together with 30 yr discharge records, were used by the Puerto Rican Aqueduct and Sewage Authority to develop a system for water withdrawal from streams that met human demands while minimizing loss of migrating freshwater shrimp (Benstead et al. 1999, March et al. 1998).

Ecologists will increasingly have to consider their own role in the decision making process. "Bet-hedging" large uncertainty may involve choosing policies that are relatively insensitive to uncertainty, that increase the ability of the ecosystem to continue to provide services even if a surprise occurs, or both. Ecologists pursue research to increase information, but they can also help develop options that maintain the capacity of ecosystems to provide services. For example, maintaining local species diversity and heterogeneity of land cover may stabilize regional primary production despite uncertain changes in climate. Limnologists have shown that optimal loadings of nutrients to lakes decrease if the information content of ecological forecasts is accounted for (Carpenter et al. 1999). In considering ways of coping with eutrophication, ecologists have discovered a diverse set of correctives that offer managers a number of options (NRC 1992).

In situations where uncertainties are large and impossible to quantify, information content is necessarily low, and decisions can be complex. Rarely can policies directly target an outcome. Instead they are often designed to affect outcomes by influencing choices made by vast numbers of people. The effects can extend beyond their intended targets and even have countervailing impacts. For example, restrictions on tree harvest in one region can lead to intensified harvesting elsewhere, as trade offsets local scarcity. Environmental restrictions can thus lead to export of environmental hazard from one jurisdiction to another.

When people can react to anticipated change, it is appropriate to explore scenarios, which are as consistent as possible with current scientific understanding, yet they are not predictions (Raskin et al. 1998, Nakicenovic 2000). Sets of scenarios are constructed to embrace the range of ambiguous and uncontrollable drivers, such as climate or globalization of markets, and nonlinear and unpredictable dynamics, such as the reflexive responses of people. Scenarios provide insight into drivers of change, implications of current trajectories, and options for action. Alternative policies can be considered in light of contrasting scenarios, to compare their robustness to possible futures.

Ecologists may inform decisions as part of an integrated perspective of vulnerability to extreme events and their potential consequences. For example, the tragic human toll of Hurricane Mitch in Central America was exacerbated by degradation due to overexploitation of fuels and construction materials. Ecologists could have foreseen that the floods of Hurricane Floyd would release hog waste into North Carolina rivers and sounds. Ecological forecasting may target the vulnerabilities that decision makers must consider, if the not the events themselves.

Next steps

Linking science with decision making will depend on scientific accuracy and on effective communication and education. Two broad classes of recommendations address these goals. First is the definition of forecasting priorities through dialog that involves scientists, managers, and policy makers. The process should consider the benefits from ecological forecasting and costs of business as usual. The priorities should meet the needs of a user clientele, they should consider scientific feasibility, and they should consider communication to general audiences, to assure effective use of forecasts and their uncertainties.

The second recommendation involves definition of a science agenda that includes i) identifying the coarse scale data needs, ii) developing models to efficiently simulate complex spatial processes, and iii) setting priorities for estimation, propagation, and communication of uncertainty and for determining the reliability of forecasts. Focus should be on the problems for which forecasts are now possible, and those that are not presently forecastable but could become forecastable within a decade.

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