Spatially explicit tools for understanding and sustaining inland water ecosystems

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In response to worldwide environmental crises driven by declines in the availability or quality of freshwater, ecologists and water resource economists are searching for ways to collaborate in order to guide the difficult choices facing the public, land managers, and politicians. Scientists are challenged to detect and quantify both the drivers of ecosystem change and ecosystem responses, including positive and negative feedbacks that will determine the future states of inland waters. Predicting ecosystem shifts over large temporal and spatial scales has proven difficult or impossible, even in well-studied systems, where the drivers of change are known. New remote-sensing, monitoring, and tracer technologies, however, offer glimpses of watershed processes at unprecedented spatial and temporal scales. Several interdisciplinary groups, including scientists, information specialists, and engineers, are exploring the best ways to design sampling schemes using these new technologies, to interpret the extensive, spatially explicit dynamic data they will yield, and to use these data to formulate models useful for forecasting. Economists, in turn, can use this information to design management and policy tools for sustaining critical ecosystem components and processes.

Front Ecol Environ 2005; 3(1): 47–55

No environments on Earth are more crucial to human society than the planet's inland waters, and yet these are currently the most threatened. Diversion, groundwater mining, salinization, pollution, eutrophication, and microbialization (Jackson *et al.* 2001) of inland and nearshore waters damage or destroy ecosystems and populations of native species, endanger public health, and threaten the water security of nations around the world (Brown 2003; Gleick *et al.* 1995). Global climate change, predicted to alter spatial and temporal distribution of precipitation, raise sea levels, and cause more intense storms and heat waves, will exacerbate water shortages and distribution problems (Service 2004; Hengeveld 2000; Field *et al.* 1999; NAS 2000; IPCC 2001). Over the coming decades, inland water "socioecological systems" (as defined by Carpenter *et al.* 2001) will have to adjust simultaneously to climate change, increased human density, and intensified land use.

In a nutshell:

- Over the coming decades, increased human density, intensified land use, and climate change will affect the ability of inland water "socioecological systems" to sustain crucial ecosystem services, but these responses remain difficult or impossible to predict
- Newly available mapping, sensing, tracing, and visualization technologies will enable us to detect and monitor drivers of change in inland water ecosystems with unprecedented scope and resolution
- Interdisciplinary groups of ecologists, earth scientists, information specialists, and engineers are now grappling with how to use the huge spatially explicit datasets these technologies will yield to forecast ecosystem change
- Economic research focused on the design of spatially targeted environmental policies, and on the analysis of the distributional and environmental effects of alternative policies, should capitalize on scientific progress in watershed forecasting to improve environmental management policies

Conflicts over the use of inland waters are difficult to resolve in ways that improve environmental resilience and human well-being. Yet collaborations between stakeholders, scientists, information specialists, engineers, and economists could potentially provide guidance for the hard management choices that society faces. They could help to develop : (1) consensus on goals, such as sustaining clean water supplies, native biodiversity, or commercially harvested populations; (2) scientific understanding of processes that support or threaten these goals, and of key variables that control or indicate their direction and rates of change; and (3) economic tools that influence policies and the actions of stakeholders, to protect processes that maintain desired ecosystems states or regimes (see Valiela *et al.* 2000, for a detailed, quantitative case history illustrating this approach). Each of these steps, including reaching stakeholder consensus, is fraught with challenges (Baker *et al.* 2004; Valiela *et al.* 2000; Ludwig *et al.* 1993). Scientists face the task of understanding how complex socioecological systems like inland waters will respond to change, particularly the multiple concurrent changes (Paine *et al.* 1999) that arise increasingly often as human impacts intensify. Economists and policy makers face the difficult task of

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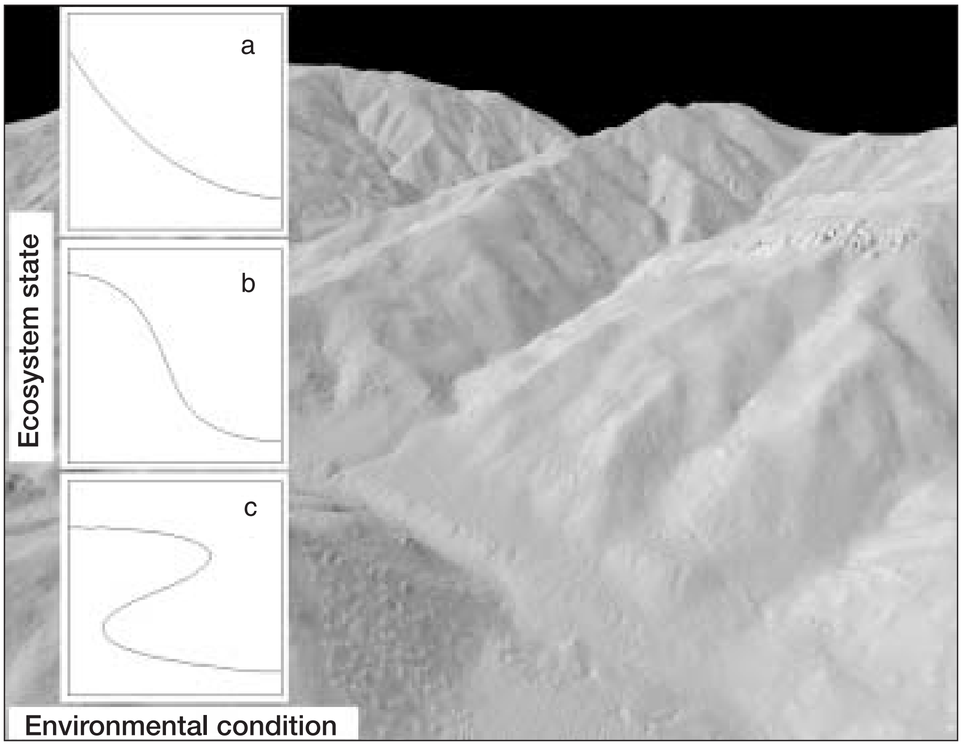

Figure 1. *Digital elevation image of the Fox Creek watershed in the South Fork Eel River (LIDAR data courtesy of WE Dietrich) and line graph from Scheffer* et al. *(2001) showing (a) ecosystem state changing continuously, (b) abruptly at an environmental threshold, or (c) by a shift at that threshold to a different "basin of attraction" in response to changing conditions. How do we apply this conceptualization to anticipate changes in a real watershed? For example, how would different amounts of timber extraction (X variable) alter water quality or fish production (Y variables) in the Fox Creek ecosystem? Would there be a gradual or an abrupt response to "the death by a thousand cuts"?*

devising flexible strategies that preserve resilience and sustain goods and services in the face of great uncertainty and rapid change, both in the systems and in our understanding of them.

Scheffer *et al.* (2001) described three ways in which ecosystems might respond to environmental change: continuously (Figure 1a), monotonically, but with a threshold (Figure 1b), or by crossing thresholds that shift states to different stable "basins of attraction" (Figure 1c). Continuous, gradual state changes (Figure 1a) seem unlikely in all but a narrow range of conditions, because of the heterogeneities, nonlinearities, and complex feedbacks intrinsic to ecological systems. If ecosystems exhibit the type of dynamics depicted in Figure 1c, conditions must be reversed well beyond the threshold that triggered the initial collapse if they are to be restored to their former state (Scheffer *et al.* 2001). Ideally, informed management would involve mapping the state of each watershed onto the appropriate Scheffer diagram, evaluating both the current position of an ecosystem and its anticipated trajectory under various scenarios of natural or managed change. In reality, this has been difficult or impossible, even when attempted with sophisticated statistical analyses applied to large datasets with long time series in very well-studied lake ecosystems (Carpenter *et al.* 1999; Peterson *et al.* 2003; Carpenter 2003).

Reflecting on the history and current status of scientific attitudes towards ecological processes and patterns might suggest a way forward. Over its 100 years of development as a science, ecology has progressed from early descriptions of patterns in nature (eg "life zones" [Holridge 1967] or "vegetational associations") to experimental studies of underlying processes in the field and in laboratory model systems (Paine 1994). From the end of the 1950s onwards, process studies and dynamics theory for species interactions and biogeochemical cycles stimulated productive interactions of observation, modeling, experimentation, and attempts at prediction (Figure 2a,b). Community ecologists focused on species interactions. Their experiments often yielded surprising results that could not have been detected without manipulations. This created deep skepticism in this community about inferring process from natural, unmanipulated patterns (Paine 1994). Such experiments were necessarily limited in scope, focusing on small spatial and temporal scales and restricted subsets of "interaction webs" (Menge *et al.* 1994; Polis *et al.* 2004). When computers came along, ecosystem ecologists created large energy or material flux models in an attempt to capture ecosystem dynamics on larger (eg watershed or regional) scales, but the data supporting these models were limited in resolution, obscuring important dynamics resulting from mechanisms such as idiosyncratic species interaction. Ecosystem and landscape ecologists have remained interested in the degree to which environmental pattern does, in fact, constrain process (Turner 1989). Due to the difficulty of gathering sufficient information on complex, dynamic natural ecosystems, ecologists in both camps have been more successful at explanations than predictions.

Part of our failure to infer causal processes from ecological patterns derives from previous limitations on our observations of these patterns and their changes over time. We are now at a point where advanced mapping, sensing, and tracing technologies are becoming practical for field research. These three technology sets allow, for the first time, extensive monitoring of ecological flows, populations, and habitat states over extended time periods. One avenue worth exploring for freshwater ecology

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would be the development of investigative approaches that capitalize on these mapping, sensing, and tracing techniques to test hypotheses about dynamic controls.

Acknowledging that longer term behavior of socioecological systems will probably remain difficult or impossible to predict, we could also use emerging technologies to monitor variables that appear to control or indicate shifts towards or away from desirable states. Below, we briefly describe several of these new technologies. We then discuss documented drivers of freshwater ecosystem change, and how new technologies may in the future facilitate the discovery of other drivers or the evaluation of their effects over time. In the final section, we discuss how economists might use new kinds of spatially explicit ecological data to devise tools and incentives, to guide the policies and actions of the stakeholders who influence and depend on inland waters.

New mapping, sensing, and tracing technologies

Recent technological innovations will make spatially explicit quantification of ecosystem processes feasible at scales relevant to organisms and ecosystem processes, often for the first time. New mapping technologies based on remote sensing (eg airborne laser mapping, see www.ncalm.ufl.edu) provide the basis for detailed topographic models from which some environmental and ecological conditions and spatial process rates can be initially deduced or hypothesized (Dietrich *et al.* 2000; Figure 2a). Ecological tracers (isotopes, trace elements, xenochemicals, genetic fingerprints) are increasingly used to track movements and histories of biota and their constituent elements (Schell *et al.* 1988; Ben-David *et al.* 1997; Ingram and Weber 1999; Power and Rainey 2000; Finlay *et al.* 2002; Schindler *et al.* 2004; Baker and Palumbi 1994). Wireless networks of stationary and mobile (www.cens.ucla.edu/portal) sensors can monitor environmental variables on small scales relevant to organisms (Estrin *et al.* 2002). Beth Burnside, a molecular biologist and Vice Chancellor for Research at the University of California, Berkeley, has commented that these new technologies may do for ecology in the 21st century what DNA sequencing did for genetics in the 20th century. These technologies have the potential to unveil the spatial dynamics of key ecosystem processes with unprecedented scope and resolution.

Researchers have never been confronted with the level of detail that these technologies can provide. Traditional "snapshots" of patterns and low-dimensional time graphs will clearly be insufficient for interpreting data of such detail and complexity. A second research area currently being explored by a number of groups (Table 1) is how ecologists, earth scientists, information specialists, and engineers can best design informative sampling schemes using these new technologies, interpret the huge spatially explicit dynamic datasets they will yield, and use these data to formulate and test models that forecast ecosystem change (see also Michener and Brunt 2000). Fortunately, parallel breakthroughs in 4-D (3-D plus time) visualization techniques (Leigh *et al.* 2003) are providing ways to create dynamic representations of spatially explicit processes that are intuitively accessible to a broad audience (Figure 2c). These would allow viewers to zoom out for overviews, zoom in to inspect particular details, and run time backwards and forwards at

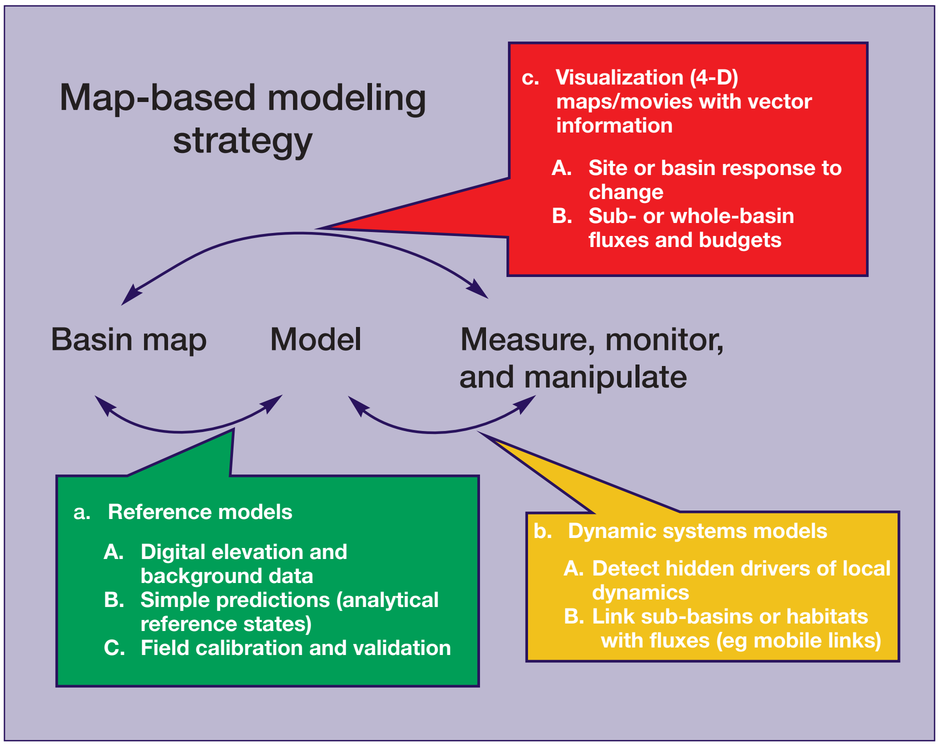

Figure 2. *Map-based modeling strategy for watershed studies used by earth scientists, engineers, and ecologists with the National Center for Earth Surface Dynamics (NCED). (a) High resolution digital elevation models are used to infer spatially varying environmental conditions and regimes, such as the probability of shallow landslides (Dietrich* et al. *2000) or stream temperature (Hondzo and Stefan 1994; Dozier and Frew 1990). Simple models (eg Fundamental Niche descriptions, Hutchinson 1957) can be used to predict distributions, abundances or performances of organisms under these environmental regimes. (b) When these fail (Schmitz* et al. *2003), local (eg food web) or regional (eg migrations or resource fluxes) dynamics can be added as needed to explain observed patterns and trends. (c) New 4-D (3-D plus time) visualization tools (eg Leigh* et al. *2003) will help scientists, economists, and stakeholders comprehend spatial dynamics (both predicted and observed) that would be obscure in more abstract depictions.*

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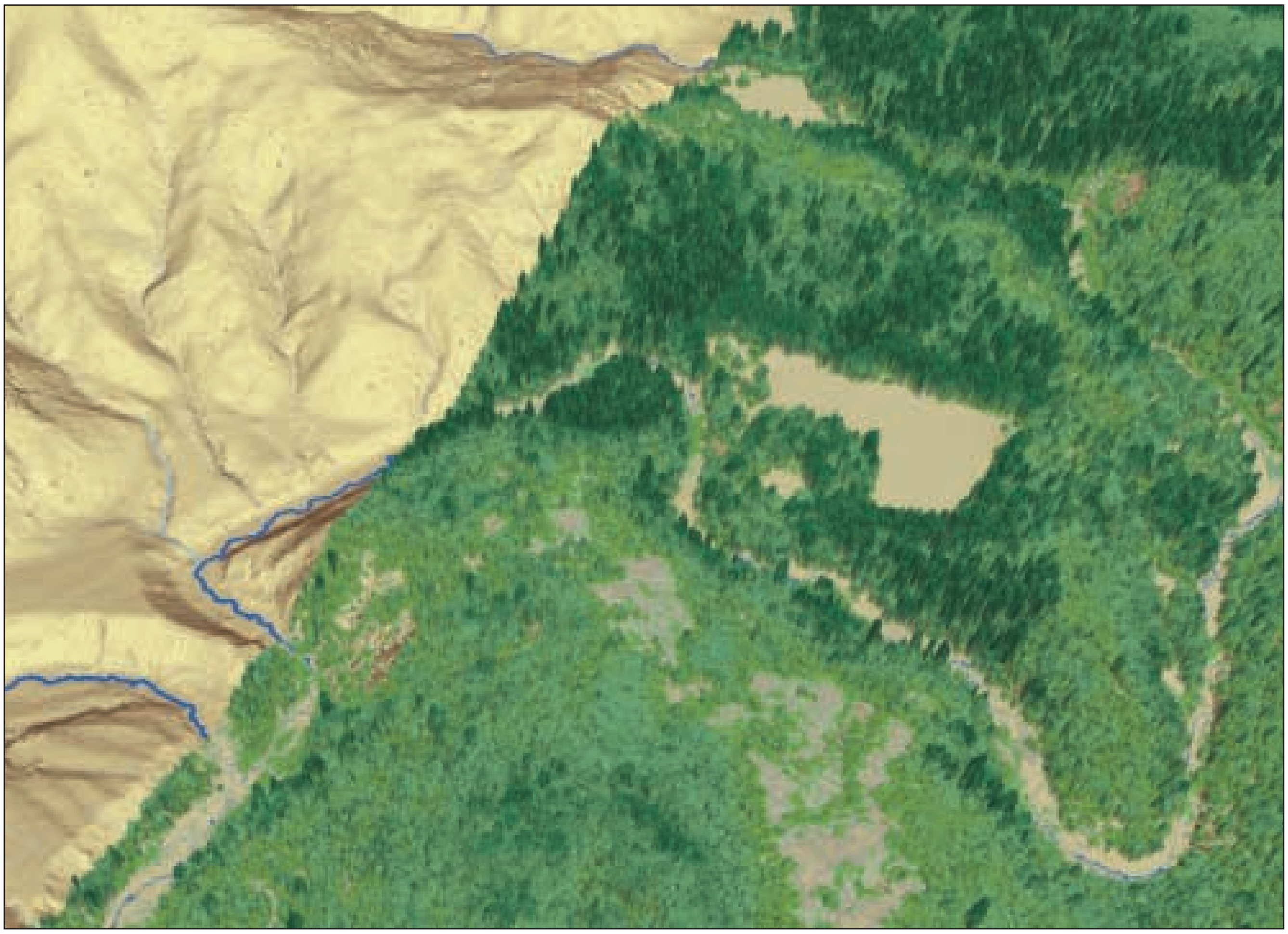

Figure 3. *Digital elevation maps (DEM) showing a section of the Angelo Coast Range Reserve, Mendocino County, CA. This 3D visualization was constructed from airborne laser swath mapping data, processed into canopy DEM, bare-earth DEM, and a stream channel network. The canopy is colored by extracting vegetation height from the difference between canopy and bare-earth DEMs. The stream channel network was draped onto the bare-earth and colored by drainage basin size. This type of dataset can provide a detailed template for launching an iterative cycle of investigation that integrates mapping, monitoring (Figure 2a), tracing, experimentation (Figure 2b), and modeling and visualization (Figure 2c). Data flown and processed by the National Center for Airborne Laser Mapping (NCALM), funded by the National Center for Earth Surface Dynamics (NCED).*

any desired speed to compare observed changes in landscapes and ecosystems with various model predictions.

Using detailed maps of watersheds and preferential flow paths of organisms, materials, and energy within and between basins (Reiners and Driese 2001) to investigate drivers of change in inland water ecosystems is not a new idea (Likens *et al.* 1977). What is new, however, is the access of scientists to mapping, sensing, tracing, and visualization technologies that can document these patterns and processes with unprecedented scope and reso-lution (Figure 3). If combined iteratively with experimental approaches that reveal key but hidden mechanisms (Figure 2b), these technologies may allow scientists to acquire the data needed at the scales necessary to evaluate

Table 1. Examples of new or currently forming interdisciplinary teams designing new approaches for large scale environmental mapping, monitoring, modeling, and forecasting

Group name	*Acronym*	*Website address*
Consortium of Universities for the Advancement of Hydrologic Science Inc.	CUAHSI	http://www.iihr.uiowa.edu/~cuahsi/his
National Ecological Observatory Network	NEON	http://www.nsf.gov/bio/neon/start.htm
Center for Embedded Networked Sensing	CENS	http://www.cens.ucla.edu
National Center for Earth-surface Dynamics	NCED	http://www.nced.umn.edu
Community Surface Dynamics Modeling System	CSDMS	http://instaar.colorado.edu/deltaforce/workshop/csdms.html

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ecosystem states, controls, and short term trajectories.

Detecting drivers of change in inland water ecosystems

Some drivers of change in inland waters, such as increased loading of nutrients or fine sediments due to human impacts on watersheds, are local and apparent. Transitions from an eelgrass- to a phytoplankton-dominated estuary at Waquoit Bay, MA, or from a clear water to a eutrophic state in Lake Mendota, WI, are driven by nitrogen (Valiela *et al.* 2000) and phosphorus (Carpenter *et al.* 1999) loading, respectively. Western rivers are degraded by land use that exacerbates the loading of fine sediments into channels (Strauss 1999; Suttle *et al.* 2004). Even where drivers of change are obvious (Figure 4), quantifying relationships between changes in loading and ecosystem response is difficult and, as previously discussed, long-term system trajectories can defy prediction (Peterson *et al.* 2003). Other ecosystem changes may have less obvious causes, including changes in hidden keystone species (Paine 1966; Power *et al.* 1996) and mobile links (Gilbert 1980; Lundberg and Moberg 2003) that connect ecosystems across habitats and sometimes across continents. Thirty years ago, snow geese migrating from the southern US to summer breeding grounds on the marshes rimming Hudson Bay imported nitrogen that balanced the amount removed by goose grazing (Bazely and Jefferies 1985). Understanding why huge areas of once productive graminoid-carpeted marshes are now turning into barren mudflats required linking a goose population surge to unsustainable densities with the conversion to agricultural land of their wintering grounds 5000 km to the south (Jefferies *et al.* 2004; Bertness *et al.* 2004). Marsh die-offs along the southeastern US may be linked to human over-harvesting of blue crabs offshore, an inference that was enabled by the detection of hidden keystone species, a snail and associated fungi (Silliman and Bertness 2002; Bertness *et al.* 2004). Cordgrass (*Spartina* spp), the dominant low marsh cover on salt marshes around the world, was thought to be inedible, entering food webs only as detritus (Odum 1970). Recently, a common snail (*Littoraria irrorata*) and the fungi that colonize its grazing scars were found to damage cordgrass lethally when the snails were released from predation by blue crabs, turtles, or fish (Silliman and Bertness 2002, 2004). Loss of their cordgrass marsh nursery could further depress crab abundance, stabilizing a new persistent state (Figure 1c) that society does not want.

Figure 4. *An urban estuary, in which the river has no access to its former floodplain. Although the local loss of floodplain services, such as storage, assimilation and detoxification of river-borne nutrients and pollutants, is obvious, impacts on coastal and offshore environments and regional (eg fisheries) resources are hard to predict, because of uncertainties related to context dependency and complex ecosystem dynamics.*

In both these studies, remote sensing and mapping technologies were useful in documenting the extent and rate of spread of the changes, but detecting the drivers required field experiments, historical analyses, and insightful natural history observations. In other ecologically important communities, such as acid mine drainage ecosystems, new genetic technologies may prove essential for detecting impacts of hidden keystones (Macalady and Banfield 2003).

In the US, 14 000 km of river are protected by the Wild and Scenic Rivers Act, but 17 000 km have been permanently poisoned by acid mine drainage (Graf 1994). Acid mine drainage is generated when aerobic water percolates through deposits of pyrite (FeS_2), the most abundant sulfide mineral on Earth. Acid and heat-loving (extremophile) bacteria, archaea, and a few fungi and protozoa (Baker *et al.* 2004) thrive in these environments, and greatly accelerate (by up to a million-fold) a rate-limiting step in the chemical reactions that generate sulfuric acid from pyrite oxidation (Singer and Stumm 1970). Information on the metabolic capabilities, roles, and interactions of microbes in acid mine drainage food webs may eventually reveal ways to reduce toxic releases to rivers.

The relative simplicity of this ecosystem (a small number of food-web members drawing energy exclusively from pyrite) has permitted the first nearly complete genomic description of a natural community (Tyson *et al.* 2004). Ecological traits and potential roles of extremophile species can potentially be inferred from annotated gene sequences. Population dynamics with short time scales and small ecosystem spatial scales facilitate experimental investigations of dynamic controls. Genomically enabled microbial ecological research holds great promise for elucidating the roles of microbes in environmental geochemistry (Macalady and Banfield 2003) and, when combined with mapping tools and sensing networks for detecting hydrologic flow paths, for guidance in managing or remediating toxic land-use impacts.

Economic analyses for sustaining inland water ecosystems

Economic tools can be used to tailor policies to match natural processes operating across landscapes and to discourage stakeholder behaviors that damage ecosystems. Scientists have viewed stakeholder education as necessary and hopefully sufficient to engender the transformation of environmental management (Costanza *et al.* 2000; Holling 2001). For example, in an Alternative-Futures analysis for the 30 000 km^2 Willamette River Basin in Oregon (Baker *et al.* 2004 and associated articles), a map-based analysis was used to project the effects of three patterns of land use on future water availability (Dole and Niemi 2004) and the ecological condition of streams (Van Sickle *et al.* 2004). The authors found that basin maps that characterized historical landscape changes and projected possible futures engaged stakeholders and gave them a perspective for evaluating the importance of projected changes (Baker and Landers 2004).

While there are cases where education and other decentralized (ie non-regulatory) environmental policies may be effective, there are also limits to moral persuasion and education campaigns. In particular, in situations where negative repercussions are separated in time and space from the actions and agents that cause them, education alone may be insufficient to lead to large-scale environmental improvement (Brouhle *et al.* 2004; Wu and Babcock, 1999). For example, it is unlikely that improved knowledge of the linkages between nutrient loading to the Mississippi River and shrimp ecology in the Gulf of Mexico will lead to farmers in the Upper Midwest reducing the amount of fertilizer they apply to their land.

Economics assumes that people pursue self-interest. Economic research has therefore focused on the analysis of incentive-based policies for the management of freshwater ecosystems. Theoretically, incentive-based systems such as taxes, subsidies, and tradable permit markets align public and private incentives for environmental benefits, and so may be superior to command-and-control systems. Moreover, most stakeholders prefer subsidies for changing their land-management practices to mandates or lawsuits. Incentive-based systems may also be introduced because they are more palatable politically. For example, in recent years, there has been a rapid growth in incentive-based agricultural–environmental programs. Such programs are expected to expand in coming years (Claassen *et al.* 2001), partly because of their acceptability to both landowners and the environmental community, and partly because they are exempt from spending limits under current World Trade Organization regulations.

While economists tend to focus on incentive-based policies and scientists on stakeholder engagement and education, in regulatory practice command-and-control policies are very common. Important examples from freshwater systems are found in many best management practices, pollutant discharge limits, and some zoning requirements such as riparian buffers. In an ideal system, where there is no uncertainty, each of these policy approaches (incentive-based, decentralized, and command-and-control) could be used to produce the same environmental outcome for the same level of expenditure. This will not be the case in situations where there is a lot of uncertainty, or political limitations that prevent the differentiation of land users with different benefits and costs of pollution mitigation activities (Hanley *et al.* 1997). The design of spatially targeted environmental policies, and analysis of the distributional and environmental effects of alternative policies, are major research areas in economics. Recent studies combining spatial environmental and economic models for managing inland water ecosystems have analyzed sediment loadings to improve water quality in Illinois (Khanna *et al.* 2003; Yang *et al.* 2003) and riparian restoration activities for maintaining in-stream temperature targets for anadromous fish in Oregon (Watanabe *et al.* 2003). These studies suggest that the spatial allocation of restoration efforts may vary (and may even switch from nearby to further reaches) as a function of environmental targets, and that riparian conditions as well as stream network structure need to be considered throughout the watershed of interest. In situations of extreme uncertainty about environmental processes and a variety of stakeholder characteristics, alternative policies may provide quite different incentives to stakeholders and have quite different effects on the environment. In particular, even though incentive-based policies and stakeholder education may provide more information about environmental processes to stakeholders than command-and-control systems, command-and-control regulations may be more efficient or cost effective (Weitzman 1974; Wu and Babcock, 2001). In most cases, command-and-control regulations achieved the objectives of the Clean Water Act, with the exception of control of animal waste (Innes 2000). Of course, monitoring and enforcement are critically important for all regulatory approaches, and command-and-control strategies are only effective to the extent that they are backed up by stiff, enforced penalties in cases of non-compliance.

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Courtesy of B Rainey

Figure 5. *The developer's advertisement "A Legacy Above it All" describes, perhaps inadvertently, how the condition of the watershed in the background will affect the health and prosperity of the future residents, and how this development will affect socioecological systems downstream.*

How should ecology and economics intersect in future research to contribute to pragmatic improvement of environmental policy? New advanced mapping, sensing, and tracing technologies should make it possible, often for the first time, to assess large-scale ecosystem responses to trial or potential management practices (Figure 5), so that changes, if needed, can be implemented before mistakes become irreversible. Having highlighted the complexity of the natural world, a major challenge for ecologists will be to provide appropriate inputs in the policy-making process, not only to help determine which types of policy work well for specific environmental problems, but also to help in modeling the potential effects of implementing realistic, politically constrained environmental policies. Rather than focus on the goal of global optimization, economics can be used to determine cost-effective policies for attaining scientifically based goals, and to analyze the distributional and equity effects of those policies. Such a decision-making framework sidesteps the controversial issue of how to place explicit monetary values on species and ecosystem services, and allows consideration of natural complexity and nonlinearities. New spatially explicit measurements and analyses will form the foundations and the testbeds for these interdisciplinary approaches.

■ Acknowledgements

We thank the University of California Natural Reserve System for maintaining a protected site for field research at the Angelo Coast Range Reserve, B Dietrich for inspiration and LIDAR and airborne laser swath mapping data, and the National Science Foundation and the National Center for Earth Surface Dynamics for funding.

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