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Scientific requirements for ecosystem-based management in the restoration of Chesapeake Bay and Coastal Louisiana

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Abstract

Ecosystem-based management requires integration of multiple system components and uses, identifying and striving for sustainable outcomes, precaution in avoiding deleterious actions, and adaptation based on experience to achieve effective solutions. Efforts underway or in planning to restore and manage two major coastal ecosystems, the Chesapeake Bay (Chesapeake Bay Program) and coastal Louisiana (Louisiana Coastal Area Plan and Gulf Hypoxia Action Plan), are examined with respect to these four principles. These multifaceted restoration programs represent among the foremost challenges for science and coastal management in the United States and, thereby, have important implications for addressing the coastal environmental crises being experienced throughout the world. Although frameworks exist for integration of management objectives in both regions, the technical ability for the quantitatively integrated assessment of multiple stressors and strategies is still in an early stage of development. Science is also being challenged to identify sustainable futures, but emerging concepts of ecosystem resilience offer some promising approaches. Precautionary management is best conceived with regard to fisheries, but should become a more explicit consideration for managing risks and avoiding unanticipated consequences of restoration activities. Adaptive management is embraced as a central process in coastal Louisiana ecosystem restoration, but has not formally been implemented in the more mature Chesapeake Bay restoration. Based on these experiences, ecosystem-based management could be advanced by: (1) orienting more scientific activity to providing the solutions needed for ecosystem restoration; (2) building bridges crossing scientific and management barriers to more effectively integrate science and management; (3) directing more attention to understanding and predicting achievable restoration outcomes that consider possible state changes and ecosystem resilience; (4) improving the capacity of science to characterize and effectively communicate uncertainty; and (5) fully integrating modeling, observations, and research to facilitate more adaptive management.

Keywords: Ecosystem-based management; Integration; Sustainability; Resilience; Precautionary approach; Adaptive management; Chesapeake bay; Coastal louisiana

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1. Introduction

Progressive concepts of "ecosystem-based management" (EBM) emphasize four common principles, namely that effective management must: (1) be integrated among components of the ecosystem and resource uses and users; (2) lead to sustainable outcomes; (3) take precaution in avoiding deleterious actions; and (4) be adaptive in seeking more effective approaches based on experience. For example, the two recent commissions charged with recommending new ocean policies for the United States stressed these elements.

The Pew Oceans Commission (2003) placed particular emphasis on the need for EBM of fishery resources and included "practice sustainability" and "apply precaution" among the guiding principles for a new ocean ethic. It further indicated that: "scientific programs should utilize adaptive management to assess results, learn from experience, and adjust incentives, regulation, and management accordingly".

The report of the presidentially appointed U.S. Commission on Ocean Policy (2004) also stressed EBM as the cornerstone of the path forward for the nation's ocean policy, meaning that management should reflect the relationships among all ecosystem components, including humans and nonhuman species and the environments in which they live. The U.S. Commission stressed that this management should balance [integrate] competing uses while preserving and protecting the overall integrity of the ocean and coastal resources and achieve sustainability by meeting the needs of the present generation without compromising the ability of future generations to meet those needs. To put these principles into practice, the U.S. Commission reported, requires aligning decision-making within ecosystem boundaries, precautionary and adaptive management, and the use of the best available science and information.

Although there may be disagreements among the definitions of and approaches to integrated, sustainable, precautionary, and adaptive management of ecosystems, few would object to the basic concepts involved. The problem is that these characteristics are more difficult to achieve in practice than to articulate in the abstract. Yet it is clear, as the U.S. Commission emphasized, that all four of these dimensions of ecosystem-based management require robust and relevant scientific information and the effective application of knowledge. While environmental scientists are generally familiar with the four principles, relatively few of us are actively engaged in directly filling their requirements. The objective of this paper is to point to ways scientific contributions can be improved in response to the emerging consensus on ecosystem-based management, not only in the U.S. but also around the world.

To advance beyond the abstract and general platitudes, I will examine a particularly pressing management challenge, namely the restoration of degraded coastal ecosystems, using as case studies the ecosystems of the Chesapeake Bay and coastal Louisiana. These examples are particularly appropriate because of their national and even international prominence, their extremely large size and complexity, and the existence of substantial organized efforts to restore them. Although physiographically different, the two ecosystems share many similar issues, including eutrophication and other consequences of landscape changes within their catchments, habitat losses, fishery declines, toxic contamination, invasive species, and navigation access. The paper builds on an earlier contribution (Boesch, 2001) with expanded and updated evaluation. My objective is to identify paths forward, through which science may more effectively address the needs of management for integration, sustainability, precaution and adaptation.

2. Four key management principles

2.1. Integration

Integration as used by the management and policy community, as in Integrated Coastal Management (ICM), generally implies collective consideration of the uses of products and services provided by the coastal environment to determine an "optimal mix". As Knecht and Archer (1993) pointed out the integration required is itself multidimensional: intergovernmental, intermedium (air, land and water), intersectoral (among users), and interdisciplinary. Integration, from this ICM view, is centered on balancing competing human uses, as reflected in the U.S. Commission on Ocean Policy's (2004) principle of "multiple use management", but the Commission adds that managing multiple human uses should be done "while preserving and protecting the overall integrity of the ocean and coastal environments".

The U.S. Commission uses the term "ecosystem-based management" rather than "ecosystem management" (Christensen et al., 1996) to accommodate human uses while preserving ecosystem integrity, or the similar concept of ecosystem health as used by the Pew Oceans Commission (2003). A recent consensus statement by marine scientists (COMPASS, 2005) takes a somewhat reversed perspective, defining the goal of EBM as maintaining an ecosystem in a healthy, productive, and resilient condition so that it can provide the services humans want and need. From these scientists' point of view, EBM should explicitly account for the interconnectedness within the ecosystem, recognizing the importance of interactions between many target species or key services and other non-target species; acknowledge interconnectedness among ecosystems, such as between air, land and sea; and integrate ecological, social, economic, and institutional perspectives, recognizing their strong interdependences.

Human uses obviously have consequences to ecosystems in addition to the direct conflicts among these uses. Furthermore, changes in ecosystems resulting from some human uses affect other human uses and behaviors. And application of EBM can have profound social and governance implications (Hennessey and Soden, 1999). For these reasons, analysts are increasingly envisioning humans and the natural world as inextricably linked in "socioecological systems" (Carpenter

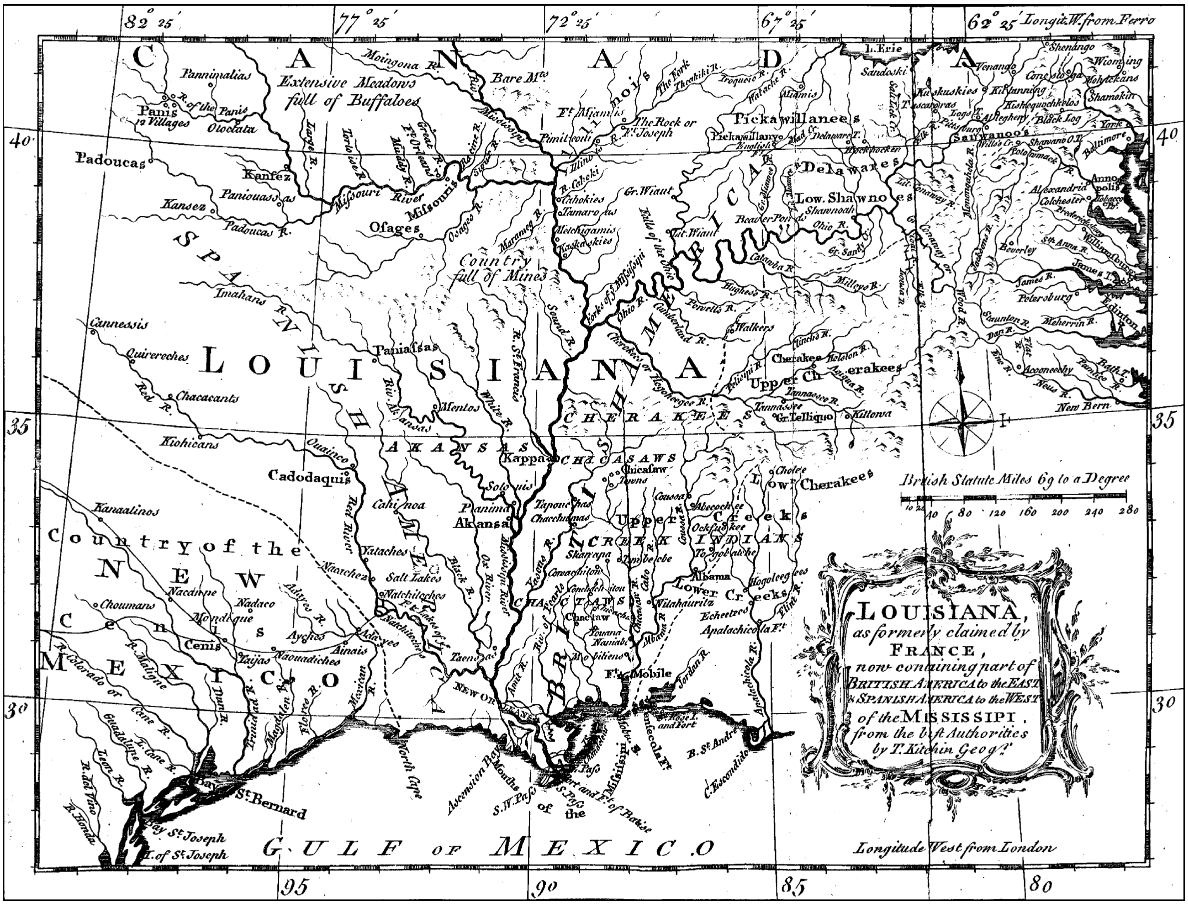

Fig. 1. The coastal ecosystems of Louisiana and the Chesapeake Bay are heavily influenced by what happens on the land, as illustrated by this 1765 map by English cartographer Thomas Kitchens. The map shows the vast extent of the rivers of the Mississippi River basin draining to the Gulf of Mexico, which interdigitate to the east with the upper reaches of the great tidal rivers of the Chesapeake Bay and Ablemarle and Pamlico sounds on the Atlantic coast.

et al., 2001) in which changes in ecosystems and human institutions are linked in their dynamic, and even cyclic, behavior (Holling et al., 2002).

Managing coastal ecosystem restoration almost always involves addressing multiple stressors that have changed the ecosystem to an undesirable state. These typically include habitat changes, excessive inputs of toxic or biostimulatory materials, alterations in the delivery of fresh water and sediments from land to the coastal ecosystem, and the consequences of living or non-living resource extraction. The effects of non-indigenous species, human-induced hydrological changes and land subsidence, and climate change may also be important challenges to ecosystem restoration in some regions. However, management as well as science traditionally addresses one stressor at time. Even in ecosystems where one is paramount, the others are can seldom be ignored.

Furthermore, many coastal ecosystems, and particularly the two addressed in this paper (Fig. 1), are heavily influenced by human activities well inland, far removed from their shores. Restoration of coastal ecosystems at the terminus of such large drainage basins requires scientific assessment and management scope that transcends many boundaries: ecological, social, and political (Jickells et al., 2001). How, then, can we make progress for science and management in integrating stressors and the human behaviors that cause them over such large regions?

2.2. Sustainability

"Sustainable" is a word frequently used with implied, but not carefully defined, meaning. The Brundtland Commission stressed the important intergenerational aspect of the concept by defining sustainable development as "satisfying present needs without compromising the ability of future generations to meet their own needs" and this intergenerational requirement is, as related earlier, encompassed in the perspective of the U.S. Commission on Ocean Policy. In its Agenda 21, the United Nations Conference on Environment and Development (UNCED) promoted even more demanding social requirements for sustainable development, calling for economic development needed to sustain and improve the quality of life of human populations (i.e. sustainable economically and socially) that is environmentally sustainable and equitable among groups in society and nations, and does not foreclose options of future generations (Cicin-Sain, 1993). The Pew Oceans Commission (2003) simply stated that "the essence of sustainable development is using our planet's resources as if we plan to stay".

Achieving sustainability is interdependent with the other management characteristics considered here. Costanza et al. (1998) espoused six principles for sustainable governance of the oceans: responsibility, scale-matching, precaution, adaptive management, full cost allocation, and participation. Matching the scales of governance to those of ecological problems and full-cost allocation necessarily depends on effective scientific integration as discussed above. The principles of precaution and adaptive management are discussed later.

Given the rapidly expanding human population, increasing per capita consumption of many resources, and the already substantial and growing human domination of Earth's ecosystems (Vitousek et al., 1997), it is difficult to be sanguine about the prospects of achieving sustainable development. However, the National Research Council (1999) concluded, based on analysis of persistent trends and plausible futures, that a successful transition toward sustainability is possible over the next two generations, even without miraculous technologies or drastic transformations of human societies. This transition will require "significant advances in basic knowledge, in social capacity and technological capabilities to use it, and the political will to turn this knowledge and know-how into action".

Toward that end, Kates et al. (2001) offered core questions for sustainability science, including knowledge of lags and inertia in natural and social systems, long-term trends reshaping these systems, their vulnerability or resilience, meaningful limits or boundaries beyond which there is increased risk of serious degradation, and effective incentive structures. They also stressed the importance of operational systems for monitoring and reporting on conditions in order to navigate a transition toward sustainability and better integration of research planning, monitoring, assessment, and decision support for adaptive management and societal learning.

Restoration of coastal ecosystems in the developed world, where populations are relatively stable, knowledge is advanced, and social capacity and technological capabilities are substantial, offers a compelling opportunity for the journey to sustainability. In the case of the coastal ecosystems we are trying to restore, it is certainly the case that their deterioration has been due to unsustainable human activities. The intergenerational consequences of these activities—dredging of oyster reefs in Chesapeake Bay and Atchafalaya Bay or completely constraining the lower Mississippi River, for example—were either not realized or were disregarded because of more immediate socioeconomic requirements. How then can we, at least on regional scales, reverse this previous track record, avoid such unsustainable practices in the future within an already greatly altered landscape, and repair the damages in a lasting way?

After decades of overexploitation of marine fisheries, we now try to restrict fishing pressure so as not to exceed optimum sustainable yields. By estimating Total Maximum Daily Loads, we are working to reduce inputs of pollutants so that water quality standards needed to support designated uses are not exceeded. For some estuaries, allocations of freshwater inflows are being made in order to sustain reproductive success of fishes. Such approaches do not specifically integrate among ecosystem functions and services, however, and a more comprehensive dimension of sustainability is emerging with growing attention to ecosystem resilience as a management objective.

Resilience is commonly defined as the capacity of a system to undergo disturbance and maintain its functions and controls. It can be measured by the magnitude of disturbance the system can tolerate and still persist (Gunderson, 2000; Gunderson et al., 2002). In addition to serving as a metaphor related to sustainability, resilience is both a property of dynamic models and a quantity that can be measured based on three properties: (a) the magnitude of disturbance that can be absorbed before the system is restructured with different controlling variables and processes; (b) the degree to which the system is self-organizing; and (c) the degree to which the system can build capacity to learn and adapt (Carpenter et al., 2001). In this sense "system" refers to the socio-ecological system and implicitly includes society and its institutions.

A paradigm is emerging that restoration strategies should have as an important, if not central, objective the recovery and maintenance of a desired level of ecosystem resilience in its performance and delivery of goods and services. However, as Gunderson et al. (2002) point out, the stability domains of ecosystems are dynamic and variable. As ecosystems degrade and lose previous resilience characteristics, the new state may become quite resilient (e.g. a eutotrophic lake) and can only be restored by altering the forces that shape the stability domains (Fig. 2).

2.3. Precaution

The precautionary principle states that if the consequences of an action are potentially adverse, the action should not be allowed to proceed, even if cause

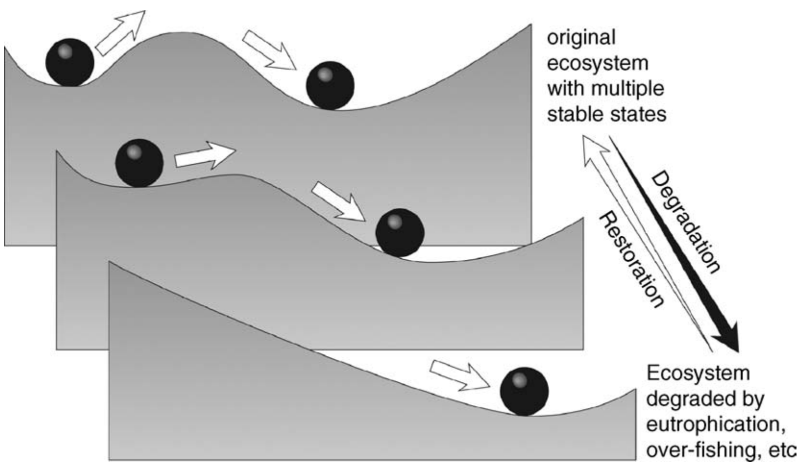

Fig. 2. Ecosystem degradation can change the stability domain of ecosystems with multiple stable states to one with only one stable domain. Restoration involves reshaping the stability domains that increase ecosystem resilience (modified from Gunderson et al., 2002).

and effect relationships have not been fully established scientifically. This principle had its origins in multinational conferences in the 1980s that addressed the discharge of chemicals into the North Sea. It has since been applied or debated relative to a broad array of issues where there is risk and uncertainty, including persistent pollutants, fisheries management, species extinction, genetically modified organisms, disease transmission, food safety, and climate change (Tickner, 2002). A precautionary approach has been embraced in variety of policy instruments from the UNCED Agenda 21 to the Magnuson-Stevens Sustainable Fisheries Act.

The precautionary principle has been criticized as impractical, requiring too high a requirement for certainty and as focusing excessively on new technologies or activities and less on those that have caused the problems we already have. To the degree to which a precautionary approach is interpreted to mean “do not take chances”, it could be an impediment to undertaking restoration actions for which the outcomes are uncertain and to pursuing experimental, adaptive management approaches (Boesch, 1999).

The U.S. Commission on Ocean Policy (2004) calls for a more balanced precautionary approach “that weighs the level of scientific uncertainty and potential risk of damage as part of every management action”. Such an approach would apply judicious and responsible management practices, based on the best available science and on proactive, rather than reactive, policies. As the Commission stated: “where threats of serious or irreversible damage exist, lack of full scientific certainty shall not be used as a justification for postponing action to prevent environmental degradation”. A challenge for science, then, is to collect information and create knowledge that conveys the range and probabilities of outcomes and expresses the associated uncertainties with those predictions. An interesting example of combining expert judgment, including the magnitude of uncertainty, and stakeholder values is provided by Failing et al. (2004).

2.4. Adaptation

Adaptation is a dimension of ecosystem-based management necessitated by the inherent uncertainty in our predictions about the natural world, socioeconomic developments, and the outcomes of management actions. New understanding, experience, and changing societal expectations inevitably mean that priorities, goals and approaches must change. Europeans refer to the iterative cycle of environmental policy adjustment the DPSIR framework, meaning the interconnection of driving forces, pressures, states, impacts, and responses (Turner et al., 2001).

In the U.S. the concept of adaptive management has developed as a more structured approach to allow managers to take action in the face of uncertainties, enhance scientific knowledge to reduce the uncertainties, and respond to unanticipated events (NRC, 2004b). Adaptive management involves implicitly learning by doing and treating management programs as experiments, with a great emphasis on accounting for outcomes, but it is not simply a “trial and error” process (Lee, 1999). Adaptive management requires: (a) management objectives that are regularly revisited and accordingly revised; (b) models of the system being managed; (c) a range of management choices; (d) monitoring and evaluation of outcomes; (e) mechanisms for incorporating learning into future decisions; and (f) a collaborative structure for stakeholder participation and learning (NRC, 2004b). Applications can range from “passive” adaptive management, which focuses on monitoring and evaluating outcomes from a particular policy option, to “active” adaptive management, which includes experiments to test competing models of system behavior or alternative solutions.

Adaptive management is particularly being planned or applied to coastal ecosystem restoration involving hydrological readjustments, such as in the San Joaquin-Sacramento delta, coastal Louisiana, and Everglades. It may be particularly suited to large, complex ecosystem restoration efforts that entail considerable risk and uncertainty, multiple objectives and phased implementation. Adaptive management has been embraced by the Corps of Engineers for ecosystem restoration and recommended by both ocean commissions. However appealing, though adaptive management is still very much a work in progress often beset with lack of clear understanding of its processes, reservations about its risks, and failures to meet requirements for monitoring and assessment (Walters, 1997). This presents many challenges to science in terms of development of appropriate models, effective design and timely interpretation of monitoring, and active engagement with decision-makers and stakeholders.

3. Background on the ecosystems

3.1. Chesapeake Bay

The Chesapeake Bay is the largest estuary in the United States and one of the largest in the world. Its main stem is 332 km long, with tidal waters extending over 11,400 km^2 and 12,870 km of shoreline. The Chesapeake drainage basin covers 166,000 km^2 in six states. The bay is relatively shallow (mean depth 6.5 m); therefore the area of its catchment is unusually large in comparison to the estuarine volume. This, coupled with its modest tidal exchange, makes the bay very susceptible to inputs of fresh water, sediments and dissolved materials from the land (Horton, 2003).

Approximately 16 million people live in the Chesapeake basin, with the largest concentrations at the tidal headwaters of estuarine tributaries around the Washington, DC, Baltimore, Richmond, and Norfolk metropolitan areas. The bay includes important commercial and military ports and is a valuable recreational resource. Although a number of the historically important fisheries (particularly oysters) have declined, the bay still supports commercial fisheries worth approximately $1 billion per year. The estuary is also heavily used for domestic and industrial waste disposal, with about 5000 point-source discharges into the estuary or drainage basin.

The Chesapeake ecosystem has undergone substantial human-induced changes since colonization by Europeans almost 400 years ago, including increased sedimentation resulting from clearing of its previously forested watershed. During the period of agrarian expansion extending into the early 19th century, more plant nutrients—forms of nitrogen and phosphorus that the native forests efficiently retained—also began to wash down into the Bay, subtly altering its natural production and food web. Industrialization later in the 19th century increased pollution, particularly by trace metals, and provided the mechanical means to exploit the abundant oysters, effectively strip-mining the extensive reefs that gave the bay its Algonquin name, *Chesepiook* or "great shellfish bay". The mid-1900s brought on the petrochemical period of the Bay's history, bringing manufactured organic chemicals, such as pesticides, petroleum by-products, and industrially produced fertilizers.

Although there were cumulative, human-induced changes in the Chesapeake Bay through the early 20th century, during the later part of that century the estuary experienced an even more dramatic state change from a relatively clear-water ecosystem, characterized by abundant plant growth in the shallows, to a turbid ecosystem dominated by abundant microscopic plants in the water column and stressful low-oxygen conditions during the summer (Hagy et al., 2004; Kemp et al., in press). This state shift was largely due to the dramatic increase in nutrient inputs in the form of wastes from the growing population, runoff of agricultural fertilizers and animal wastes, and atmospheric deposition of nitrogen oxides resulting from fossil fuel combustion. By the mid-1980s the Chesapeake Bay was receiving about seven times more nitrogen and 16 times more phosphorus than when English colonists arrived (Boynton et al., 1995). In addition, the drastic depletion of the once prodigious oyster populations and loss of wetlands and riparian forests diminished important sinks for nutrients and sediments within both the watershed and the estuary.

In the 1970s the scientific community began to understand and document the pervasive changes in the ecosystem that had taken place and to identify their causes. This led to growing awareness by the public and political leaders, which in turn resulted in the evolution of regional management structures and restoration objectives (Hennessey, 1994; Boesch et al., 2001a,b). Starting with a simple agreement in 1983 "to assess and oversee the implementation of coordinated plans to improve and protect the water quality and living resources of the Chesapeake Bay estuarine systems," the three primary states in the region, the national capital district and the federal government formed the Chesapeake Bay Program and have issued a series of directives and agreements related to reductions of nutrient and toxicant loadings, habitat restoration, living resource management, and landscape management.

Because eutrophication was seen as the most pervasive and consequential human impact, a landmark agreement of the Chesapeake Bay Program was the 1987 commitment to reduce controllable inputs of nitrogen and phosphorus entering the bay by 40% by the year 2000. As that year approached it was clear that this goal would not be reached and, furthermore, a complex array of interrelated issues related to environmental quality, living resources, and human activities

Table 1
Goals of the proposed Chesapeake 2000 Agreement (Chesapeake Bay Program, 1999b)

1. Restore, enhance and protect the finfish, shellfish, and other **living resources**, their habitats and ecological relationships to sustain all fisheries and provide for a balanced ecosystem.
   Oysters: tenfold increase
   Exotic species: identify and reduce introduction
   Fish passage: restore passage in blocked rivers
   Multi-species management: develop and revise management plans
   Crabs: restore health of spawning population

2. Preserve, protect and restore those **habitats** and natural areas vital to the survival and diversity of the living resources of the Bay and its rivers.
   Submerged aquatic vegetation: recommit and raise previous restoration goal
   Wetlands: achieve net gain through regulatory protection and restoration
   Forests: protect and restore riparian forests
   Stream corridors: encourage local governments to improve stream health

3. Achieve and maintain the **water quality** necessary to support the aquatic living resources of the Bay and its tributaries and to protect human health.
   Nutrients: achieve and maintain 40% goal and reduce further to protect living resources
   Sediments: reduce loading to protect living resources
   Chemical contaminants: no toxic or bioaccumulative impacts on living resources
   Priority urban waters: restore urban harbors
   Air pollution: strengthen air emission pollution prevention programs
   Boat discharges: establish “no discharge zones”

4. Develop, promote and achieve **sound land use** practices which protect and restore watershed resources and water quality, maintain reduced pollutant loadings for the Bay and its tributaries, and restore and preserve aquatic living resources.
   Land conservation: protect and preserve forests and agricultural lands
   Public access: expand public access points
   Development, redevelopment and revitalization: reduce rate of land development
   Transportation: coordinate with land use planning to reduce dependence on automobiles

5. Promote **individual stewardship** and assist individuals, community based organizations, local governments and schools to undertake initiatives to achieve the goals and commitments of this agreement.
   Public outreach and education: provide information about Bay to schools and public
   Community engagement: enhance small watershed and community-based actions
   Government by example: develop and use government properties consistent with goals

Specific objectives and actions under each goal are briefly summarized.

needed to be addressed in a more comprehensive manner. The Chesapeake 2000 Agreement was reached, which includes over one hundred goals and commitments that together comprise one of the most ambitious ecosystem management programs for a large coastal area (Table 1).

Progress in restoring the Chesapeake Bay ecosystem has been mixed. Although eutrophication is no longer growing, there is a very public debate concerning the amount of nutrient load reductions that have been achieved (Whoriskey, 2004) and few clear signs that the symptoms have been alleviated, except locally. The concentrations of a number of potentially toxic substances (some trace metals and chlorinated hydrocarbons) in sediments and organisms declined as a result of source controls and waste treatment. Yet, the industrialized harbors in the bay remain heavily contaminated and other subregions show elevated concentrations of toxicants or evidence of biological effects. Seagrasses have returned in some regions but cover only a small portion of the habitat occupied in the 1950s. Oyster (*Crassostrea virginica*) populations have not recovered because of the degraded reef habitat and ravages of two microbial pathogens. Populations of several anadromous fishes have increased modestly as a result of removal of barriers to upstream migration. Perhaps the most dramatic recovery has been for populations of striped bass (*Morone saxatilis*), which greatly increased as a result of a multi-year moratorium on harvest and subsequent, more precautionary management of stocks. On the other hand, the very productive blue crab (*Callinectes sapidus*) fishery has shown some decline and signs of recruitment over-fishing.

3.2. Coastal Louisiana

The coastal ecosystems considered here are at least as extensive as the Chesapeake Bay, but less well-defined. They include the two provinces of the Louisiana Coastal Area (LCA), the Mississippi Deltaic Plain and the Chenier Plain to the west (Boesch et al., 1994), and the adjacent inner continental shelf. The Deltaic Plain consists of the mostly inactive distributaries of the river and extensive tidal wetlands, swamps, and lagoons lying between the distributaries or enclosed by fringing barrier islands. The Chenier Plain developed as a result of the interplay of three coastal plain rivers and the longshore transport of sediments escaping the Mississippi-Atchafalaya delta system. The inner continental shelf, which has estuary-like salinity gradients, stratified water masses, and significant physical and biological interactions with the LCA, should appropriately be included as an effective part of this large coastal ecosystem. This expansive wetland-estuarine-shelf ecosystem supports one of the richest fisheries in the U.S., large populations of migratory birds, and the substantial majority of the coastal and offshore oil and gas production in the United States. It is one of the most economically important coastal regions of the country, with \$20 billion annually in oil and gas and fisheries production alone, and one of the most threatened.

The catchment of the Mississippi River is vast, over 3.2 million km^2, including 41% of the conterminous United States and even a small part of Canada. It encompasses all or part of 30 of the 50 United States, from the arid west toward the Rocky Mountains to the humid forests of the Appalachian Mountains to the east. The north-central part of the basin, originally prairies, forests, and wetlands, has been extensively converted to cropland that produces most of the corn, soybeans, wheat, sorghum, and livestock grown in the United States. While 70% of the flow from the Mississippi basin is discharged through its well-recognized birdsfoot delta, projecting into the Gulf of Mexico, the remaining 30% (regulated by law) flows down the only other significant distributary presently active, the Atchafalaya River, which enters the Gulf of Mexico 230 km to the west.

The average annual discharge of water through the Mississippi and Atchafalaya rivers to the coastal ecosystem is approximately 20,000 $m^3\,s^{-1}$, essentially an order of magnitude higher than freshwater discharge into the Chesapeake Bay. The hydrology of this vast river system has been greatly altered by locks, dams, reservoirs, earthwork levees, channel straightening, and spillways for purposes of flood protection, navigation and water supply. These alterations have significantly affected the transport of water, sediments and dissolved materials (including nutrients and toxic contaminants) in ways that have major consequences to the coastal ecosystem (Turner and Rabalais, 2003).

Disruption of overbank flooding in the delta, widespread hydrological modifications caused by myriad canals, and high rates of subsidence (because of the huge thickness of alluvial deposits), locally accelerated by fluid withdrawals associated with oil and gas production have conspired to result in rapid loss of tidal wetlands, particularly during the last half of the 20th century. Over 4850 km^2 of coastal land, mainly tidal wetlands, have been lost since the 1930s (Barras et al., 2003). Although the annual rate of loss has slowed somewhat from a peak in the 1970s, it is estimated to have been approximately 62 km^2 between 1990 and 2000, with a projection of 26 $km^2\,y^{-1}$ over the next 50 years. Various efforts have been mounted to stem the loss of coastal wetlands, including more restrictive permitting of dredge and fill activities and restoration projects undertaken under the auspices of the federal Coastal Wetlands, Planning, Protection and Restoration Act (CWPPRA). Steps toward a more comprehensive approach to restoration were taken with the development of the report "Coast 2050: Toward a Sustainable Coastal Louisiana" (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 1998). This has been refined in a Louisiana Coastal Area ecosystem restoration study that recommends a plan of action (the LCA Plan) to Congress (U.S. Army Corps of Engineers, 2004).

A more recently recognized problem is the extensive seasonal hypoxia in bottom waters on the continental shelf (Rabalais et al., 1996, 2002b). Hypoxic (<2 mg L^{-1}) bottom waters have extended over 10,000 to 20,000 km^2 in the summer during most years since

1990. This phenomenon and other manifestations of eutrophication have been related to the increases in nutrient loading by the Mississippi-Atchafalaya river system. In particular, flux of nitrate-N from the Mississippi Basin to the Gulf of Mexico has averaged nearly 1 million metric tons per year since 1980, about three times larger than it was 30 years ago (Goolsby et al., 1999). The majority of the increased nitrate emanates from agricultural sources in the upper Mississippi and Ohio river basins, over 1500 km upstream of the discharge into the Gulf of Mexico.

In response, the U.S. Congress directed the government to conduct an assessment of the causes and consequences of hypoxia in the Gulf of Mexico, including analyses of the potential for reduction of nutrient sources and associated economic costs. The resulting integrated assessment (CENR, 2000) presents much more comprehensive evidence concerning nutrient sources, trends and effects on oxygen depletion for the Mississippi-Atchafalaya delta system than existed at the initiation of the Chesapeake Bay Program and its commitments for nutrient reduction, approximately 15 years earlier. Subsequently, a task force representing eight federal agencies, nine states, and two tribal governments adopted an Action Plan (Table 2) for reducing the area experiencing hypoxia by two-thirds (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001; Rabalais et al., 2002a); however, measures to implement this agreement have not progressed much at this point.

In addition to wetland loss and eutrophication, ecosystem-based management of the Mississippi delta region must also address significant issues in fishery management (including overfishing of some stocks, bycatch mortalities due to shrimp trawling, commercial and recreational fishery conflicts, and endangered species concerns); flood protection; navigation; oil and gas exploration, production and transportation; and migratory waterfowl management.

4. Current state of practice

I now provide brief perspectives on the extent to which these two ambitious coastal restoration efforts have used science in applying the four principles of ecosystem-based management: integration, sustainability, precaution, and adaptation. Using these examples I will then consider how science can make more effective contributions for advancing these four critical dimensions of informed management.

Table 2
Goals and principles of the Action Plan for Reducing, Mitigating and Controlling Hypoxia in the Northern Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001)

	Goals
Coastal Goal	By 2015, subject to available resources, reduce the 5-year running average areal extent of the hypoxic zone to less that 5,000 km^2 through implementation of specific, practical and cost-effective voluntary actions by all jurisdictions and categories of sources to reduce the annual discharge of nitrogen into the Gulf.
Within Basin Goal	To restore and protect the water of the 31 States and Tribal Lands within the Mississippi/Atchafalaya River Basin through implementation of nutrient and sediment reduction actions to protect public health and aquatic life as well as reduce negative impacts of water pollution in the Gulf of Mexico.
Quality of Life Goal	To improve the communities and economic conditions across the Mississippi/Atchafalaya River Basin, in particular the agriculture, fisheries and recreational sectors, through improved public and private land management and a cooperative, incentive based approach.

Principles
1. Encourage actions that are voluntary, practical and cost effective
2. Utilize existing programs, including existing State and Federal regulatory mechanism
3. Follow adaptive management
4. Indentify additional funding needs and sources during the annual Agency budget process; and
5. Provide measurable outcomes as outlined in the three goals

The plan attempts to integrate goals in the Gulf of Mexico with those of environments and communities within the river basin.

4.1. Integration

The U.S. Commission on Ocean Policy (2004) pointed to the Chesapeake Bay Program as a model for regional ecosystem-based management. Indeed, the Chesapeake 2000 Agreement goes far beyond the original focus of the program on water quality with actions to address habitat, living resources, sound land use within the watershed, and even individual stewardship. A hallmark of this program is the setting of ambitious quantitative goals and timelines. For example, the 2000 Agreement calls for conserving and restoring forests along 70% of streams in the watershed, restoring 10,000 ha of wetlands, preserving 20% of the land area from development, and increasing the stretches of rivers open to migratory fish by 2184 km by specific dates, mostly by 2010.

Quantitative understanding and models support some of the relationships among these elements of the ecosystem. For example, the Chesapeake Bay watershed model predicts the effects of changes in land use and management practices on delivery of nutrients and sediments to the estuary and from this a three-dimensional eco-hydrodynamic model forecasts changes in water quality, including clarity, chlorophyll and light levels, in the estuary. Using these tools one can forecast with some level of confidence how, for example, the restoration of forested riparian buffers at specified places in the watershed should affect nutrient loading and environmental conditions in the bay. Furthermore, these linked models can be run in the inverse mode to determine the regional allocation of load reductions needed to achieve the water quality requirements of important living resources (U.S. Koroncai et al., 2003). However, many other relationships among actions, goals and environmental outcomes in the Chesapeake 2000 Agreement are, at best, integrated only through a qualitative conceptual framework. In particular, the restoration of water quality is presumed to yield significant positive benefits to fisheries production, but quantitative evidence for this relationship remains sketchy (Kemp et al., in press).

The evolving ecosystem-based management of coastal Louisiana has involved integration at several levels. The integrated assessment of Gulf hypoxia (CENR, 2000) involved the analysis of: atmospheric inputs of nutrients from data collected to monitor acid deposition; land-use characteristics; water quality data from throughout the basin and statistical models to estimate fluxes by river segment; and box models of nutrient and carbon budgets in the Gulf of Mexico. The fact that different modeling approaches are used to predict the extent of Gulf hypoxia yielded generally similar results boosts confidence in the assessments (Scavia et al., 2004), just as does the convergence of climate model predictions of global warming sensitivities (Kerr, 2004). Complex, deterministic models similar to those for the Chesapeake Bay and watershed are lacking for the Mississippi basin and continental shelf, however simpler and more empirical models may be sufficient to guide the integration of management of the vast watershed with the management of coastal ecosystems. While many improvements can be made in models and their uses, both the Mississippi River assessment and the Chesapeake Bay models are leading examples of the power of systemic science for large system management. Such integrated assessment and modeling have helped managers and scientists alike to think across environmental media, disciplines, and sectors (e.g. agriculture, environmental quality and living resources).

To support the LCA Plan development, a team of scientists and engineers undertook extensive hydrological and ecological modeling to predict the consequences of various restoration measures and ensembles on salinity, wetland nourishment and land building, habitat suitability for various resource species and water quality (U.S. Army Corps of Engineers, 2004, Appendix C). Net benefits for the multiple scenarios were estimated and the relative benefits related to costs in the selection of preferred alternatives. The effort involved ambitious integration of understanding of physical, geological, and biological processes, with an explicit articulation of ecosystem services expected from the predicted outcomes. Among those services considered was nutrient removal from river water reintroduced into interdistributary wetlands and estuaries (Lane et al., 1999) that could contribute to the alleviation of continental shelf hypoxia. Although such diversions would remove only a small part of the total nitrogen load of the Mississippi River, properly located and operated river diversions could be a component of a basin-wide nutrient management strategy (Mitsch et al., 2001) as well as contribute to coastal wetland restoration.

A principal impetus in the call for ecosystem-based management in the ocean commission reports

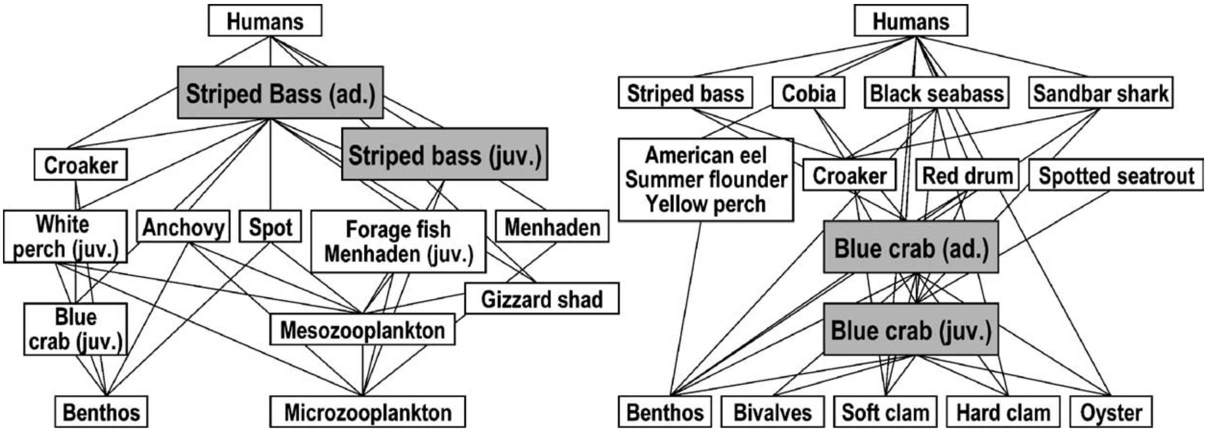

Fig. 3. Sub-food webs for the striped bass (*Morone saxatilis*) and blue crab (*Callinectes sapidus*) in Chesapeake Bay (McBride and Houde, 2004).

is the failure of fishery management based solely on species-by-species considerations. For any given species the interactions among predators (including humans) and prey, incidental mortality (bycatch), and habitat requirements are highly complex (Fig. 3). For multiple fishery species the task of integration is daunting. This has led to the development of theory and tools for multi-species and, ultimately, ecosystem-based management of fisheries resources (Browman and Stergiou, 2004). These approaches have emphasized dynamics of populations and the interactions among predators and prey (top-down) rather than the biogeochemical drivers (bottom up) stressed in the models previously discussed.

The Chesapeake 2000 Agreement includes a commitment to move toward multi-species management of fisheries and there has been ongoing development of scientific approaches (Miller et al., 1996; Latour et al., 2003) that would lead to a Chesapeake Bay fisheries ecosystem plan (McBride and Houde, 2004). Analytic approaches include expansion of single species models to multispecies virtual population analysis and models of trophic interactions such as Ecopath with Ecosim (Pauly et al., 2000). Similar network analytical approaches that consider a broader array of interactions within the ecosystem have provided insights into the critical functions that have to be addressed in ecosystem restoration (Baird and Ulanowicz, 1989; Baird et al., 2004). Efforts are underway to link the eco-hydrodynamic model developed to predict Chesapeake Bay water quality with Ecopath models to estimate the consequences of nutrient load reductions on fishery species. As the complexity of linked models grows, however, it becomes more important to avoid putting all the eggs in one basket. Multiple, less complex models may be more nimble, advance learning more quickly, and result in more practical and routine applications.

Comprehensive ecosystem-based management must eventually integrate the consequences of multiple stressors that confront these ecosystems, including eutrophication, toxic contamination, habitat modification, fishing, invasive species, climate change, alterations of freshwater inflow, coastal land use changes, and natural disturbances such as storms and freshets. These stressors interact in important ways. For example, trace metals and organic contaminants have been shown to affect the quantity and quality of algal production in enriched waters (Breitburg et al., 1999). Conversely, eutrophication-induced oxygen stresses influence the immunological responses of marine animals to toxicants and pathogens (Lenihan et al., 1999). Unfortunately, our scientific and management institutions are not well aligned to facilitate the integration of multiple stressors in ecosystem-based management. Scientific subcultures, as maintained by journals, societies, and conferences, tend to focus on one issue (e.g. toxins, wetlands, nutrients, fisheries, hydrology) or on one biotope (estuaries, rivers and streams, forests, agriculture, and urban environments). At best, management is generally

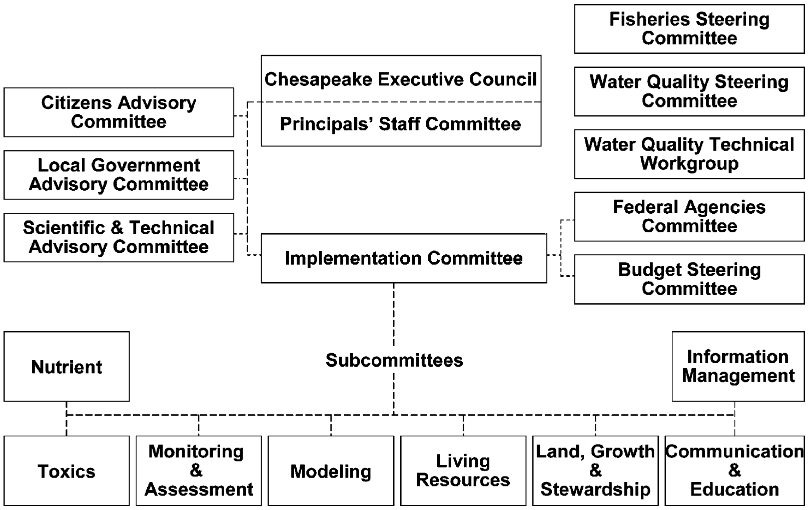

Fig. 4. Organizational chart of the Chesapeake Bay Program.

integrated only at higher levels and not very effectively at the technical levels. For example, in the Chesapeake Bay Program technical subcommittees of the Implementation Committee (Fig. 4) operate more-or-less independently.

A major challenge in both regions is the integration of environmental and fisheries management, especially because an important goal in both of these environmental restoration programs is the improvement and protection of living resources. Recently, the effects of fishing have received much attention as a major cause of coastal ecosystem degradation (Jackson et al., 2001). Cascading, top-down effects of selective removal of predators, heavy mortality of species included in incidental bycatch, and physical effects of resource extraction (e.g. bottom trawling in Louisiana and oyster dredging in the Chesapeake Bay) all may have significant consequences. However, it is not particularly helpful to stress the primacy of fishing effects in comparison to other stressors (Boesch et al., 2001a,b), particularly in the two ecosystems in question.

Although it is generally thought that environmental degradation (hypoxia and other effects of eutrophication and wetland and other habitat modification) has diminished the capacity of these ecosystems to sustain healthy fisheries, this relationship is in fact very poorly quantified or understood in both cases. Yet, unraveling the interrelations is essential for ecosystem-based management and effective restoration. Comparisons of recent and historic composition of fish caught in trawls on the Louisiana inner continental shelf (Chesney and Baltz, 2001) and Lake Pontchartrain (O'Connell et al., 2004) illustrate the point. Shrimp trawling, eutrophication and hypoxia increased between the earlier period of the record to the present. In both cases the catch-per-unit-effort (CPUE) of several species of bottom dwelling fish has declined, while the CPUE of certain pelagic, plankton feeders has increased (Table 3). To what degree is this a result of bycatch mortalities or the effects of trawling on bottom sediments, nutrient enrichment or hypoxic stress? As a step in the direction of integrated management of the environment and fisheries, Haas et al. (2004), after examining the relationship between marsh edge and growth and survival of juvenile brown shrimp (*Farfantepenaeus aztecus*), argued that management should be extended from the traditional protection of the spawning stock through catch regulations to protection of estuarine life stages through habitat conservation and restoration.

In these two regions and throughout the world, environmental management cannot be conducted detached from the pressures of socioeconomic development. The economic importance of agricultural production in the upper Mississippi Basin and the role of the region in the global food supply are potent forces that constrain the options for controlling nutrient inputs into the Gulf (Turner and Rabalais, 2003). Similarly, accommodating population growth and land develop-

Table 3
Changes in the relative abundance (catch per unit effort) in trawl fishery bycatch species off the Louisiana Coastal Area between 1933 and 1989 studies (Chesney and Baltz, 2001)

Species	Water-column distribution	Relative CPUE	
		1933	1989
Anchoa mitchelli (bay anchovy)	Pelagic	29.9	55.7
Brevoortia patronus (Gulf menhanden)	Pelagic	14.1	26.9
Cynoscion arenarius (sand seatrout)	Demersal	25.1	17.7
Micropogonias undulatus (Atlantic croaker)	Demersal	207.4	16.0
Arius felis (sea catfish)	Demersal	15.1	10.6
Leisostomus zanthurus (spot)	Demersal	8.3	4.4
Polydactylus octonemus (Atlantic threadfin)	Nektonic	8.7	1.8
Etropus crossotus (fringed flounder)	Demersal	3.8	1.7
Bairdiella chysura (silver perch)	Demersal	4.1	1.6
Trichiurus lepturus (cutlassfish)	Epi-demersal	11.6	1.5
Trinectes maculatus (hogchoker)	Demersal	7.2	0.7
Selene setapinnis (Atlantic moonfish)	Epi-demersal	8.3	0.6
Menticirrhus americanus (Southern kingfish)	Demersal	4.1	0.6
Stellifer lanceolatus (star drum)	Demersal	30.6	0.3
Peprilus burti (Gulf butterfish)	Nektonic	4.3	0.1

ment in the expanding information economy of the Mid-Atlantic region present challenges for Chesapeake Bay restoration (Boesch and Greer, 2003). Moreover, restoration of delta wetlands has to contend with the realities of providing flood protection, navigational access and oil and gas extraction. A variety of scientific approaches help illuminate these relationships, e.g. the agricultural economic modeling conducted in the Gulf of Mexico integrated assessment (CENR, 2000) or the economic-land use-watershed models that project water quality changes in the Patuxent subestuary of the Chesapeake (Costanza et al., 2002). However, robust ecological-socioeconomic models capable of guiding coastal ecosystem management and social development toward a harmonious future remain a distant objective.

4.2. Sustainability

The state of Louisiana's grand vision for addressing wetland loss was entitled "Coast 2050: Toward a Sustainable Coastal Louisiana" (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 1998) and the LCA Ecosystem Restoration Study (U.S. Army Corps of Engineers, 2004) mentions "sustainability" or "sustainable" no fewer than 63 times. Sustainability is used to refer to the coastal ecosystem, habitats, wetlands, resources, geomorphic features, landscapes, deltaic functions, restoration approaches, and even the regional economy. Interestingly, the Chesapeake 2000 Agreement, although admittedly a much shorter document, mentions sustainability only three times, all in the context of land uses (Chesapeake Bay Program, 1999).

It is no surprise, with the rapid and seemingly irreversible changes to the coastal landscape of Louisiana, that the public, policy makers, and managers would seek sustainability. However, there are limits to achieving a permanent, static solution in such a clearly dynamic ecosystem. Indeed, if anything dramatic change has been the secret to success for the Mississippi Deltaic Plain. The LCA plan seems to recognize this in its critical needs assessment criteria, which include restoring fundamentally impaired deltaic functions through river reintroductions and preserving geomorphically important landforms, in addition to preventing future land loss and protecting vital socioeconomic resources. Furthermore, the plan specifically targets restoration activities that could be sustained in the face of relative sea-level rise by introducing sediments from the Mississippi River.

Even though the Chesapeake Bay Program has not as explicitly addressed sustainability, the concept is implicit in many of its commitments. Objectives for water quality improvements through reduction in nutrient and sediment loadings have long included the notion that once these goals are achieved they will be maintained (targeted loadings would be capped) even in the face of population growth and development. Many of the Program's commitments to sound land use and stewardship and community engagement were developed to address sustainability. Achieving sustainable yields has long been a stated, but seldom achieved, goal of fisheries management and managing harvest levels to maintain the "stability" of living resources is an explicit expectation of the Chesapeake 2000 Agreement. One outcome of the Agreement's call to "manage the blue crab fishery to restore a healthy spawning biomass, size and age structure" has been bi-state agreement on fishing pressure reductions necessary to ensure more sustainable exploitation (Bi-state Blue Crab Advisory Committee, 2001).

Resilience is not at all mentioned in either in the LCA Study or in the Chesapeake 2000 agreement, but could provide a very powerful restoration objective for both cases. The journalist Tom Horton (2003) devotes a whole chapter of his semi-popular book "Turning the Tide: Saving the Chesapeake Bay" to resilience. Horton makes the point that the Chesapeake Bay has lost much of its resilience in maintaining its function and recovering quickly from disturbances, such as floods and other climatic extremes because of human-induced changes not only in the bay but through out the watershed. He identifies as primary culprits the reduced coverage and increased fragmentation of forests; the loss of wetlands; the development and hardening of shoreline; the degradation of benthic communities including submersed grasses, oysters, and sediment dwelling organisms; and the blockage of rivers to migratory fish. Water now flows more rapidly from the landscape, carrying more sediment and nutrients. Furthermore, these loadings are less effectively attenuated by nontidal wetlands, most of which have been lost. Also, the estuarine ecosystem itself has a diminished capacity to modulate the effects of these loadings because of impairments at its margins and in its benthic realm.

Put in terms of resilience theory, the Chesapeake ecosystem has transitioned to a new system state with its own stability basin—one characterized by more turbid conditions, phytoplankton-microbe dominance, and less efficient support of upper trophic levels that may be quite resistant to change (Fig. 2). As a result, the broader ecosystem, including the watershed, has considerably different resilient properties that it did, certainly compared to pre-colonial times, and even fifty years ago. It might, therefore, be useful to consider restoration of this ecosystem not as a linear process, but as one that involves reshaping the stability domain of the present system to achieve another system state that has the desirable properties that Horton writes about. One would expect this restored ecosystem to be "healthier" in terms of its vigor, organization and resilience (Mageau et al., 1995; Boesch, 2000).

Resilience could also be an important management objective for coastal Louisiana ecosystem restoration. How might restoration of wetlands and riparian forests in the river basins improve the resilience of the coupled basin-shelf to seasonal hypoxia? What approaches to coastal wetland and barrier island restoration are most resilient to hurricanes and other extreme events? How might river reintroductions be designed and managed to promote the "self-design" of wetlands, which are resilient in the face of subsidence and sea-level rise?

Defining the requirements for sustainability involves making predictions about the future that go beyond an understanding of present conditions or even reconstructing the changes that led to the degradation of an ecosystem. However, developing predictions based on thorough knowledge of past changes in the ecosystem, present functions and trends, and models that incorporate effects of alternate management actions can provide powerful perspectives on what Carpenter (2002) called "the long now" and, thereby, on the requirements for sustainable solutions. To a certain degree, the strategic models developed for determining required reductions in nutrient loadings or estimating the effects of restoration features on future wetlands embody this approach. However, these models are typically constrained by short time horizons (generally subgenerational rather than intergenerational) and limited consideration of unmanaged drivers, such as climate change, population growth, and socioeconomic development, such that they cannot fully address sustainability. Development of multiple plausible scenarios that illustrate the consequences of both management and societal decisions over the long term may help illuminate the requirements for sustainability (e.g. Boesch and Greer, 2003).

4.3. Precaution

The Chesapeake 2000 Agreement incorporates the notion of precaution explicitly with regard to living resources management, indicating: "we will manage harvest levels with precaution to maintain their health and stability and protect the ecosystem as a whole". Precaution or precautionary are mentioned over 50 time in the fisheries ecosystem plan (McBride and Houde, 2004) in which the "precautionary approach" is defined as "a type of fishery management that exercises prudent forethought to avoid undesirable outcomes with respect to stock status, yield potential, or profitability. This approach accounts for changes in fisheries systems that are only slowly reversible, difficult to control, not well understood, and subject to changing environment and human values".

Precaution is also implicit in other Chesapeake 2000 management commitments. For example, regarding potentially toxic chemical contaminants it states: "Through continual improvement of pollution prevention measures and other voluntary means, strive for zero release of chemical contaminants from point sources". Much like the original development of the precautionary principle for North Sea chemical discharges, this commitment is based on strong risk aversion.

Precaution has been less explicitly been considered as an integral element of management for the Louisiana coastal ecosystem. Given the massive legacy of the unintended consequences of agricultural development, river management, flood protection, navigation, oil and gas extraction, and fisheries exploitation in this ecosystem, it should be more specifically addressed. While many of the restoration measures considered in the LCA Plan are designed to correct for or reverse the unintended consequences of past actions, they may have unintended consequences themselves. The phasing of the LCA Plan seems to take this into account advancing programmatic authorization for restoration features that meet a sorting criterion based on sufficient scientific and engineering understanding of processes, while holding others for additional evaluation, pilot project testing, and more detailed study of long-term, large-scale concepts. Further, the plan calls for a Science and Technology Program that would focus on reducing uncertainties, including those related to: (1) physical, chemical, geological, and biological baseline conditions; (2) engineering concepts and operational methods; (3) ecological processes, analytical tools, and ecosystem responses; and (4) socioeconomic/political conditions and responses.

Because many of the management challenges in these two regions involve undoing changes to the ecosystem rather than consideration of a new addition or human activity, the precautionary approach is usually being applied in the inverse of how it was originally proposed for North Sea dumping, i.e., what are the consequences of not correcting a problem. However, a conventional challenge for precautionary management currently exists regarding the possible introduction of a nonnative oyster species, *Crassostrea ariakensis*, into the Chesapeake Bay (National Research Council, 2004a). Such an introduction is being proposed by the states of Maryland and Virginia because this species seems to be able to grow well under the environmental conditions found in the bay and resist lethal diseases that currently limit recovery of the native *C. virginica*. Interestingly, the introduction is proposed not only for revitalization of the fishery, but also for restoration of the role that oysters played in filtering eutrophic waters, thereby helping to recover the resilience in the ecosystem. Extensive research is underway to address critical questions in a risk assessment framework, but in the end the decision will be highly dependent on the level of precaution applied. What is the burden of proof concerning potentially deleterious effects that may be largely irreversible? How will the uncertainties be weighed in the decision? And how do contemporary socioeconomic factors affect the determination of appropriate precaution?

4.4. Adaptation

Adaptive management has been embraced very explicitly in the Gulf hypoxia Integrated Assessment (CENR, 2000) and Action Plan (Rabalais et al., 2002a,b) and in the LCA Plan for coastal wetland restoration (U.S. Army Corps of Engineers, 2004). Adaptive assessments of the monitoring have been conducted on completed CWPPRA projects, yielding lessons learned that could be incorporated into LCA restoration measures. In addition, existing reintroductions of river flow into the wetlands have been operated in "experimental" modes in which flow rates are varied or pulsed, again producing valuable information for future design and operation of diversions. Nonetheless, in the draft LCA Plan adaptive management is relegated to an activity of the Science and Technology Program (U.S. Army Corps of Engineers, 2004), rather than fundamentally ingrained in the ecosystem restoration program itself. While its emphasis on explicit expectations, monitoring, and learning provides an overall philosophical model and framework for integrating modeling, monitoring and research, adaptive management does have its practical limits for such a large ecosystem as coastal Louisiana, where many potential interventions are costly and relatively irreversible. For example, although one can certainly learn valuable lessons from monitoring the small-scale river diversions currently in place in the delta, the expense and social dislocations involved in massive river diversions require that they be considered as more than just "experiments".

In contrast to coastal Louisiana and other major ecosystem restoration programs heavily dependent on water management, such as for the Everglades, San Francisco Bay and Sacramento-San Joaquin Delta, and Upper Mississippi River (NRC, 2004b), adaptive management is not an explicit framework or formal process in the Chesapeake Bay Program. However, earlier in its history, Hennessey (1994) viewed the Chesapeake Bay Program as a good example of adaptive management of a large ecosystem in that it has adjusted goals based on experience and information. On the other hand, I (Boesch, 1996, 2001) noted the Program's shortcomings in emphasis on structured learning, pursuit of multiple options in the face of uncertainty, and close interaction between models and monitoring that are the hallmarks of adaptive, as opposed to "trial and error" or reactive, management (NRC, 2004b). The application of adaptive management approaches is discussed in the Chesapeake fisheries ecosystem plan (McBride and Houde, 2004), but most Chesapeake Bay regional managers and scientists, alike, remain largely unfamiliar with adaptive management and its requirements.

Under adaptive management, practitioners must be explicit about what they expect and they must collect and analyze information so that expectations can be compared with actuality. They must periodically correct errors, improve their imperfect understanding, and change actions and plans. The coupling among explicit expectations (from modeling), comparisons with actuality (through monitoring), and changed actions and plans is the essence of adaptive management. The Chesapeake Bay Program has extensive and advanced environmental and monitoring programs, but they are relatively weakly linked in either periodic or ongoing assessments of progress. For example, a State of the Bay report (Chesapeake Bay Program, 2002) asserts: "Throughout the 1980s and 1990s, we made real progress toward our goals of improving the Bay's water quality and reducing pollution. A recent analysis revealed that between 1985 and 2000, phosphorus loads delivered to the Bay from all of its tributaries declined by 8 million pounds per year. Nitrogen loads declined by 53 million pounds per year". First, the monitoring results summarized elsewhere in the report provides scant evidence of actual water quality improvements in the bay. In addition, the analysis referred to is based on monitoring of direct point source discharges together with unverified model estimates of the more significant nonpoint discharges, which assumes of the complete and immediate effectiveness of management practices applied. Not only is this reliance on models designed for strategic forecasts in progress assessment misleading, as suggested in a front-page *Washington Post* article (Whoriskey, 2004), but failure to rigorously compare loadings via streams and rivers to model projections misses adaptive learning opportunities that could help refine models, improve monitoring, and, most importantly, reassess the effectiveness of management strategies.

Both models and monitoring are critical to adaptive management, but, in evaluating 25 adaptive management planning exercises for riparian and coastal ecosystems, Walters (1997) found that ongoing modeling that strives for ever-increasing detail and complexity tended to supplant monitoring, field experimentation and the alternate models needed for adaptive management. Walters also noted that it is "depressingly easy" for scientists to convince themselves, and funding agencies, that "fundamental understanding" of the process or mechanism that they study is somehow important for refining models to make predictions about impacts of ecosystem management policies. The Chesapeake Bay Program has stressed the big model culture. In coastal Louisiana multiple, simpler models have been used both for wetland restoration (U.S. Army Corps of Engineers, 2004, Appendix C) and hypoxia assessments (Scavia et al., 2004) because these were the only approaches feasible at the time. Calls now being made there for "more sophisticated", complex hydrodynamic models should be greeted with caution.

The implementation of an adaptive approach to ecosystem restoration faces many practical challenges, including convincing the stakeholders to participate in experiments; sustaining effective monitoring programs in the face of waning interests and other priorities; interpreting the ambiguous outcomes likely in complex and uncontrolled ecosystems; and resistance to changes in management approaches. Nonetheless, it is it is clear that our understanding, goals and priorities do evolve over time. It stands to reason that embracing some form of formally adaptive structure would assist in the orderly and effective evolution of ecosystem-based management.

5. Paths forward

Although I admit bias from my experience, which has predominantly been in the two ecosystems in question, I believe that the efforts to restore the Chesapeake Bay and coastal Louisiana ecosystems present among the foremost challenges for science and coastal management in the United States and, thereby, have important implications for addressing the coastal environmental crises being experienced around the nation and throughout the world. The imposing scales of these two coastal systems and associated watersheds are obviously one reason for my thinking this. The two ecosystems also are confronting a plethora of environmental challenges—virtually every problem being experienced elsewhere and then some—that require integrated solutions through ecosystem-based management. These two systems have been the archetypical models for scientific understanding of estuaries and river deltas, respectively. In the case of the Chesapeake Bay, the strength of the science, public support and financial capacity create a "best case scenario" for large-scale ecosystem restoration. If it cannot be done here, can it be done anywhere? On the other hand, coastal Louisiana enigmatically contains perhaps the nation's most economically valuable and most imminently threatened coastal region. And, both systems stretch the imagination, much less the capacity, for comprehensive management over large watersheds with multiple jurisdictions of governance.

From this review of current status of the restoration of these two coastal ecosystems, I offer the following suggestions to improve the contributions of science in advancing integration, sustainability, precaution and adaptation as practical dimensions of ecosystem-based management. Acting on these suggestions will require major changes in the way business is done by active scientists, organizations that support science, and decision makers.

- Greater scientific attention should be directed to providing the solutions needed for ecosystem restoration. While scientists have been remarkably successful in documenting the historical changes in these two coastal ecosystems and in diagnosing the causes of ecosystem degradation, we are less well adept at prescribing solutions. Solution science confronts a scientific culture that offers incentives for detachment and disincentives for engagement. Given the urgency of the world's problems, scientists must become more engaged interacting with decision makers and informing the public (Lubchenco, 1998; Palmer et al., 2004). Environmental scientists should become well versed in the concepts of integration, sustainability, precaution and adaptation and seek ways to contribute to their practical application in ecosystem-based management. While it is important that vibrant programs of basic, curiosity-driven research are sustained, sponsorship of solution science should be greatly expanded. Peer review should be modified to allow innovation, but terminate support for superficially appealing research on ineffective solutions. Better integration of research planning, monitoring, assessment and reporting on conditions is required (Kates et al., 2001). Human health-related research has successfully fostered excellent science and solution science for many years and can serve as a model for new management-oriented, ecosystem research programs.
- Bridges should be built that cross scientific and management barriers to the integration required for ecosystem-based management. While the complete merger of scientific disciplines and management responsibilities is both unlikely and unwise, concerted efforts are required to bridge the formidable barriers to effective integration. Providing financial incentives, e.g. targeted funding for integrative research and assessments, is likely to be most effective. Broadening interdisciplinary graduate and professional training, coalescing technical committees, and focusing conferences, workshops and assessment teams on key integration problems could also help. Boundary organizations that are effective at communication, translation, and mediation because

of their credibility, salience and legitimacy (Cash et al., 2003) should be built and sustained. These could include special centers, committees and coalitions.

- More attention should be given to understanding and predicting achievable restoration outcomes that consider possible state changes and ecosystem resilience. Research and assessment should evaluate degradation tipping points and restoration thresholds. Greater support should be provided and institutional arrangements revised to foster predictive approaches and provide a solid scientific basis for the selection and maintenance of achievable and desirable outcomes, which effectively provide desired services in the combination of conserved, restored and invented ecosystems that will characterize our human-dominated coasts of the future (Palmer et al., 2004).
- Science should improve its capacity to characterize, if not quantify, uncertainty in assessments and predictions and to effectively communicate this uncertainty to managers and the public. Improvements in this area are critical if the precautionary approach is to move beyond rhetoric and opinion into practical application.
- Modeling, observations, and research should be fully integrated to facilitate adaptive management. Development and comparisons of multiple models should be encouraged; exclusive reliance on complex, monolithic models should be avoided. Progress should be assessed or verified by observations and the relationships between model projections and observations should be used to assist in the interpretation of observations (whether and why they deviate from projections), refinements of models and improvements of the observing systems.

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