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Destructive Fishing Practices and Evolution of the Marine Ecosystem-Based Management Paradigm

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"The greatest and noblest pleasure which man can have in this world is to discover new truths; and the next is to shake off old prejudices." Prussian King Frederick II (The Great) (1712–1786)

"Doubtless, it is because of the youthfulness of fishery biology itself that the methodology of fishery conversation has so little developed." Elmer Higgins (1934)

Abstract. The recent increase in interest about effects of trawling and dredging on seafloor ecosystems and their fisheries can be understood by examining three phases in the history of conservation thinking. The primary focus in nonmarine conservation thinking and management worldwide is on maintaining biodiversity, while marine managers are still focused mainly on use of marine life. Marine conservation lags behind nonmarine conservation, as shown using key measures of scientific publication, species protection, and ecosystem protection. Because fishing is the human activity that most affects marine biodiversity, marine fisheries biology has a particularly large role in determining the fate of the sea's biodiversity. Unlike management-oriented nonmarine fields including wildlife biology and forest biology, marine fisheries biology has yet to incorporate key insights from the science of ecology, including the importance of maintaining abundance and diversity of predators and structure-forming species. Growing concern about the loss of structure-forming species, such as corals and sponges, and their role in providing fish habitat cannot be addressed using traditional stock assessment techniques. This creates the need for the evolution of a new marine ecosystem-based management paradigm that incorporates modern understanding of ecology and conservation biology.

Introduction

Conservation evolves in response to new understanding about the workings of nature and ways that individuals and institutions affect it. The pace of conservation evolution has increased rapidly in recent decades, paralleling rapidly increasing awareness of the damage to nature caused by human activities. New scientific fields have been spawned and gained thousands of recruits, including conservation biology and restoration ecology. Conservation's theoretical framework, public awareness, laws (see Bean and Rowland 1997 for a useful overview of U.S. wildlife laws), and government programs evolved first in nonmarine realms, but the increasing harm to the marine realm now compels marine scientists, legislators, managers, users, and conservation advocates to devise new ways to conserve what people value in the sea.

Having been trained as a marine ecologist but having received "battlefield commissions" in marine and forest conservation biology, I have observed how both terrestrial and marine conservation thinking and practice have evolved. Here, I summarize the evolution of conservation as a backdrop for examining the marine management paradigm that most impacts life in U.S. waters, focusing specifically on its effectiveness in dealing with fishing practices that disturb the seafloor. This is a topic that transcends mere academic interest because the greatest challenge humans face in the 21st century is finding ways to live on our planet without destroying its living systems (including marine systems) and their essential functions, on which we depend. Both personal experience with fisheries controversies and examination of the scientific literature and news stories indicate that there is ample reason to be concerned.

Three Stages in Conservation Thinking

To understand the present state in marine conservation, it is useful to compare it to the much longer and better-

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documented history of conservation in nonmarine systems. An astute reader will probably note intriguing parallels with conservation in marine systems as well as some significant differences.

Although the first humans who walked across the Bering Sea profoundly reduced the diversity of North America's terrestrial megafauna and altered its ecosystems (Diamond 1997; Flannery 2001), Europeans who left their biologically impoverished continent were stunned by the abundance of North America's wildlife (Kimball and Johnson 1978). They set out to subdue the new land by making full use of North America's species, including its pines *Pinus* spp. for ship masts, oaks *Quercus* spp. for ship hulls, beaver *Castor canadensis* for hats, and white-tailed deer *Odocoileus virginianus* for meat. The land itself—once bent to our use—could provide an abundance of pasturage, crops, minerals, water, and living space to fuel westward expansion. The attitudes that drove the dominant society's effects on wildlife populations were primarily ones that Kellert (1993, 2005, this volume) classifies as "dominionistic" and utilitarian: We were fulfilling a divine purpose by using everything useful that the land provided.

By the start of the 20th century, the dominant species and ecosystems of the United States had undergone profound changes. The land animal with the greatest biomass—American bison *Bison americanus*—had gone from an estimated 30–60 million (Kimball and Johnson 1978) a few decades earlier to just a few hundred individuals. The most abundant bird—the passenger pigeon *Ectopistes migratorius*—had gone from an estimated 5 billion to the edge of extinction (Blockstein 2002). American bison survived by the narrowest of margins, but the last passenger pigeon died in 1914. The three key attributes—species composition, structure, and functioning—of "virgin" forest and prairie ecosystems that had covered most of the country were almost completely altered by settlers colonizing the land. The few institutions responsible for managing our use of the land were woefully ill-equipped to deal with conservation.

America's conservation movement arose in the 19th century as the impending closing of the frontier led to growing concern about the loss of wildlife and land resources. Reflecting public attitudes, the first stage of conservation was largely utilitarian. Species conservation focused on preventing loss of species that were considered "good" because they were useful (e.g., deer and ducks) and eliminating species (e.g., wolves *Canis lupus* and mountain lions *Felis concolor*) that were considered "bad" because they ate "good" species or otherwise interfered with resource use. High trophic level species—the large carnivores—disappeared throughout large parts of their ranges, as did the biggest grazers, eastern bison and eastern elk *Cervus canadensis*. Many smaller, once-common species, such as white-tailed deer, raccoons *Procyon lotor*, and wild turkeys *Meleagris gallopavo*, were serially hunted to rarity.

At the same time, place-based conservation was driven by concern about loss of scenic and timber values needed for future recreational and industrial use, an ethic exemplified by the thinking of Gifford Pinchot (e.g., Pinchot 1947), the first head of what became the U.S. Forest Service. The U.S. federal government began protecting lands that became our National Parks and National Forests starting in the 1872 and 1891, respectively.

Early species conservation efforts focused mainly on controlling hunting mortality through bag limits (limiting the number of animals a hunter could possess), seasonal prohibitions (e.g., prohibiting hunting of deer until fawns were independent), or restricting hunting methods that were deemed too efficient or wasteful (e.g., a 1910 law prohibiting use of boat-mounted punt guns, which were large bore shotguns that could kill tens of sitting ducks with one shot (see Harvesting the River, Illinois State Museum, *http://www.museum.state.il.us/RiverWeb/harvesting/harvest/waterfowl/tools_techniques/guns/punt_gun.html*).

Long ago it became clear to nonmarine wildlife managers that controlling hunting mortality was essential but not sufficient. A landmark event in U.S. conservation was the designation of the federal government's National Wildlife Refuge system in 1903 (Lee 1986), the first of more than 500 protected areas dedicated to maintaining and recovering America's disappearing wildlife and their habitat. Another was the founding of a nonprofit organization, Ducks Unlimited, in 1937 for the purpose of protecting prairie pothole breeding and nursery habitat essential to waterfowl in the USA and Canada. Protecting habitat crucial to highly migratory species has a longstanding history in terrestrial and freshwater wildlife management.

Conserving wildlife and wildlands for their own sake, the view espoused by John Muir (Muir 1901) and Aldo Leopold (Leopold 1949), became far more prevalent as the environmental movement flowered in the years following publication of *Silent Spring* (Carson 1962), leading to the passage of laws including the U.S. Endangered Species Act (ESA) of 1973. The ESA clearly represented a major advance in conservation thinking, embracing the idea that all living things are important to conserve for their own right as well as for their utilitarian value. It embodied truly enlightened concepts, as indicated by these excerpts:

- …these species of fish, wildlife, and plants are of aesthetic, ecological, educational, historical, recreational, and scientific value to the Nation and its people….

- The term "endangered species" means any species which is in danger of extinction throughout all or a significant portion of its range…
- The Secretary shall … determine whether any species is an endangered species or a threatened species because of …(A) the present or threatened destruction, modification, or curtailment of its habitat or range…
- The purposes of this Act are to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved…

The drafters of the ESA clearly considered it crucial to protect species throughout their range whether or not they were demonstrably useful and fully recognized the importance of species' critical habitats and (still more broadly) the importance of protecting ecosystems as a whole. The ESA reflects and institutionalizes conservation ethics including those that Kellert (1993, 2005, this volume) calls scientific, aesthetic, humanistic, naturalistic, and moralistic.

However, there are three important weaknesses with the endangered species approach. The ESA applies only to species that are in serious trouble, and the burden of proof that they need protection falls on those who propose their conservation. This is analogous to having a health-care system consisting of hospital intensive care units that have dauntingly high admission standards. Thus, protection of species and habitat critical to their continued existence under ESA does not take effect until species clearly require heroic—in other words, expensive, painful, and frequently unsuccessful—conservation measures. However essential it is to keep species from "falling off the edge," preventing extinction is hardly a comprehensive, sustainable strategy. One reason is that we seldom have adequate assurance that we can save endangered species before it is too late. Another is that focusing on species that are imperiled ignores the benefits that are roughly proportional to the numbers of organisms, not merely their continued existence. These include the values of species for recreation; few people are willing to spend time searching for wildlife so rare that encountering them is vanishingly unlikely. Many benefits from living things come not only from the numbers of species but their abundance, including ecosystem services (Daily 1997), the natural functions on which humans utterly depend. These include pollination and seed dispersal, preventing proliferation of pest species, amelioration of flooding, building and maintaining soil fertility, decomposing dead plants and animals, cleansing water and air, and maintaining a climate suitable for human life. A focus on conserving endangered species fails to provide the quantitative benefits that ecologists and biogeochemists have demonstrated to result from the multiple roles of living things in the biosphere. A third weakness of the ESA approach is that it functions primarily (although not exclusively) at the species level, giving less emphasis to higher and lower hierarchical levels of biological assets.

The inadequacies of the utilitarian and endangered species stages of conservation created a need for further evolution in conservation thinking that recognizes the importance of living things as resources, and in their own right, but that neither waits until species are about to disappear nor places the burden of proof on those who want to conserve life. This third stage is a focus on maintaining biological diversity, presaged conceptually by Leopold (1949) and Myers (1979); used (in a narrow sense, clearly to mean species diversity) by Risk (1972), National Research Council (1978), Lovejoy (1980a, 1980b), and Wilson (1980); explicitly defined by Norse and McManus (1980); redefined as the term is widely used in conservation today by Norse et al. (1986); and subsequently examined from various perspectives by Wilson (1988), Reid and Miller (1989), and countless others. For those who want to delve into this topic, the evolution of biological diversity as a conservation goal is examined in Norse (1996) and Farnham (2002).

Just as the endangered species ethic does not invalidate the earlier utilitarian ethic but creates a richer, more complex and more encompassing understanding of conservation needs and strategies, the biodiversity ethic broadens and deepens both of these ethics. Conserving biodiversity is a more robust conservation ethic for four reasons:

- It is hierarchical and recognizes the importance of all three major levels of biological organization, the diversity of genes within species, the diversity among species, and the diversity among ecosystems (communities of organisms in their physical settings).
- It transcends mere presence–absence, recognizing that quantities matter.
- It deals with composition, structure, and function, both ecosystem parts and processes, focusing on maintaining the biological integrity that the public intuitively understands as "the health of nature," not merely what is immediately useful, beautiful, or otherwise popular.
- It is precautionary, focusing on maintaining and recovering diversity whether or not there is demonstrable, imminent threat.

In short, focusing on biodiversity conservation is a conceptual framework that makes it possible to conserve life for its own sake and for human benefit whether or not we can gauge the worth of a gene, species, or ecosystem to us at present. For these reasons, maintaining biological diversity has quickly become the primary focus of conservation efforts throughout the world on land and in freshwaters. A recent study (Norse and Carlton 2003) found that biodiversity is mentioned on more Internet sites than other scientific concepts or sciences including relativity, molecular biology, or oceanography. In just 24 years, biodiversity conservation has become the driving force in conservation around the world, except, ironically, in the sea.

Nonmarine and Marine Conservation

In the United States, as in much of the world, the science and practice of conservation are far more advanced on land and in freshwaters than in the sea. Consider the following disparities:

- Market hunting has been illegal for terrestrial animals and quite limited for freshwater animals for many decades; the venison, buffalo, or duck in markets and restaurants is not wild caught. In contrast, most marine wildlife in markets are wild caught; the only way most marine species are managed is by attempting to control adult mortality rather than selectively breeding them, feeding them, controlling their environment, and preventing their diseases. Even marine species (e.g., oysters, shrimps, bluefin tunas *Thunnus thynnus*) that are "farmed" are far less domesticated—that is, they differ far less anatomically, physiologically, and behaviorally from their wild relatives—than their terrestrial and freshwater counterparts.

- Terrestrial wildlife managers and conservation biologists generally estimate populations in terms of numbers of individuals, reflecting their concern about maintaining healthy populations; marine fisheries managers generally measure populations in tons, reflecting their concern about maintaining production of biomass.

- Conservation biologists have tended to overlook the sea. In the first 37 issues (1987 to1995) of *Conservation Biology*, nonmarine papers outnumber marine papers 565 to 37 (Irish and Norse 1996). In subsequent issues (December 1996 to December 2000), nonmarine papers outnumber marine papers 701 to 82.

- Large terrestrial predators are generally protected by laws, regulations, and social peer pressure. Terrestrial apex predators or other high trophic level species including wolves, grizzly bears *Ursus arctos*, big cats, and eagles that were once killed in large numbers are now revered symbols of wildness and the targets of intensive recovery programs. In contrast, many of their marine counterparts—apex predators or other high trophic level species including sharks, billfishes, tunas, and groupers (family Serranidae)—are still considered choice targets for commercial and sportfishing, activities that are subsidized by federal and state governments. Indeed, some nations (Japan, Iceland, Norway, and Canada) support commercial killing of apex predators or high trophic level species including sperm whales *Physeter macrocephalus*, baleen whales, dolphins, and pinnipeds.

- The first terrestrial plants to be protected under the U.S. Endangered Species Act, including the San Clemente Island Indian paintbrush *Castilleja grisea*, were listed in 1977; in contrast, the first marine plant, Johnson's seagrass *Halophila johnsonii*, was listed only in 1998. The first freshwater invertebrates, including the Alabama lampmussel *Lampsilis virescens*, were listed in 1976; the first marine invertebrate, white abalone *Haliotis sorenseni*, was not listed until 2001. The first freshwater U.S. fishes, including Apache trout *Oncorhynchus apache*, were listed in 1967; the first truly marine U.S. fish, the smalltooth sawfish *Pristis pectinata*, was finally listed in 2003. Indeed, the ESA currently offers protection to 746 nonmarine plants, 186 nonmarine invertebrates, and 115 nonmarine fishes but only 1 marine plant, 1 marine invertebrate, and 2 truly marine fishes.

- Laws governing consumptive uses on lands under U.S. jurisdiction are markedly different in their focus on maintaining the full spectrum of species and the resulting benefits they provide. The National Forest Management Act of 1976 (U.S. Code, title 16, sections 1600–1614, August 17, 1974, as amended 1976, 1978, 1980, 1981, 1983, 1985, 1988, and 1990), a law governing use of resources on most federally owned forestlands, requires the U.S. Forest Service to "provide for diversity of plant and animal communities based on the suitability and capability of the specific land area in order to meet overall multiple-use objectives." In contrast, its marine analogue, the Magnuson Fishery Conservation and Management Act of 1976 (U.S. Code, title 16, sections 1801–1882, 90 Stat. 331; as amended by numerous subsequent public laws listed and identified in the U.S. Code), even its 1996 reauthorized and substantially improved version, still has no such explicit mandate. Those who framed our laws on forests were thinking about diversity when those who framed our laws on oceans were not, and that has not changed even in the decades since the concept of biological diversity became the driving force in terrestrial conservation.

- The United States began designating lands that became National Parks, where most terrestrial wildlife species are protected from directed taking, in 1872 and began designating multiple-use lands, which became National Forests, in 1891. There are now 88 National Parks and 125 National Forests. In contrast, the United States began designating National Marine Sanctuaries only in 1975 and has designated only 13 to date. Moreover, few of them have strong provisions barring directed take of marine wildlife. The United States still has no special federal program that focuses on establishing fully protected marine reserves.
- National Parks (from Glacier Bay to Everglades) that fully protect terrestrial wildlife commonly allow fishing, even commercial fishing, in their marine waters.
- In the 2002 federal budget, the U.S. government is spending 67 times as much money for our National Parks and 93 times as much money for our National Forests as for our National Marine Sanctuaries despite the fact that the marine area under federal jurisdiction is not only vastly larger than the federal land base but is actually larger than the entire U.S. land area.
- Habitat restoration (e.g., restoring stream flow regimes, deliberate placement of coarse woody debris, soil amendment, and revegetation with native species) is becoming a commonplace tool for private and public management efforts of terrestrial and freshwater ecosystems. In contrast, there are few effective or large-scale efforts to restore key marine ecosystem features, the closest approximation being the dumping of unwanted materials such as oil production platforms, ships, tanks, subway cars, and tires into the sea to become "artificial reefs." As one illustration, on June 30, 2004, Googlefight.com listed 202 web sites mentioning "anadromous fish habitat restoration" versus only nine web sites mentioning "marine fish habitat restoration."
- Restoration ecologists have tended to overlook the sea. In the eight 2002 and 2003 issues of *Restoration Ecology*, nonmarine papers outnumbered marine papers 102 to 26, even when a special issue, 10(3), having 14 marine papers is included.
- In the last several decades, the U.S. Forest Service has progressively restricted clear-cutting. It is compelled to conduct area-specific environmental reviews before proceeding with each timber "sale" to be logged and requires loggers to pay the federal treasury (that is, the taxpayers who own these lands) for the privilege of extracting resources from public forestlands. In contrast, trawlers, whose impacts on structurally complex bottoms are similar to those of loggers, trawl almost anywhere they wish on federal undersea lands and pay no royalties to the treasury for the public resources they take.

It is understandable why the science and practice of conservation came later to the sea than to the land and freshwaters. Human physiology and senses are much better equipped to see and understand what is happening in those realms. With suitable shelter and clothing, terrestrial biologists can visit and study biodiversity anywhere on a permanent basis. Freshwaters are somewhat more difficult to study but are so shallow and so limited in extent that scientists can readily observe changes to all but the remotest of them (e.g., the depths of the Great Lakes and Lake Baikal). In contrast, the sea's vastness makes research inherently expensive, and the pressure in its depths makes in situ marine observation far more difficult. Indeed, many marine scientists have found that commercial interests that exploit subsea oil deposits or marine fish populations are far more numerous and better equipped than we are. In consequence, the public, lawmakers, and managers know far less about the sea's biodiversity than they know about that of the land or freshwaters. This unfamiliarity has fostered the assumption that the sea is both a never-ending cornucopia and convenient receptacle for humankind's wastes.

Scientific disciplines and management approaches that focus on maintaining biodiversity have not yet become prevailing conservation paradigms in marine ecosystems as they are on land and in freshwaters. As a result, while nonprofits and governments are putting substantial resources to arresting the decline of biodiversity on land, we protect the sea far less effectively. Marine conservation is decades behind its terrestrial and freshwater counterparts. Failure to eliminate this gap may well be the greatest weakness in U.S. conservation.

While the United States exerts management authority over a variety of economic activities within its exclusive economic zone, the fact that fishing is clearly the leading threat to the sea's biological diversity and integrity (Jackson et al. 2001; Pauly et al. 2002; Myers and Worm 2003) means that fisheries management has by far the greatest effect on marine conservation. Although all modern methods of fishing have the potential to overfish target species, the plurality of targeted catch, the majority of bycatch (Figure 1), and the majority of habitat damage is caused by fishing with mobile gear, including bottom trawls and dredges (Chuenpagdee et al. 2003; Morgan and Chuenpagdee 2003). Indeed, trawling and dredging are the most important disturbances on the world's seafloor, especially in waters below 80 m (Watling and Norse 1998). Trawling now occurs on the remotest seamounts and on continental slopes down to 2,000 m (Merrett and Haedrich 1997; Gordon 2001). Since (a) the sea is by far the largest of the Earth's three biotic realms, (b) the vast majority of marine species are benthic, (c) fishing is the greatest threat to marine biodiversity, and (d) trawling is the seafloor's most important fishing method and largest source of disturbance, trawling must have profound implications for the world's biodiversity and the sustainability of humankind's food supply. Yet, despite this, trawling impacts have received remarkably little attention from the public, lawmakers, and managers.

Figure 1. Commercial shrimp trawl catch, northern Gulf of California, Mexico. The bycatch:shrimp biomass ratio in this and other hauls that the author photographed was approximately 20:1 (Norse, Marine Conservation Biology Institute).

Much of the reason why the destructive effects of trawling are largely overlooked and why biodiversity considerations and the ecosystem approach have failed to become integral to marine conservation is the dominance of the stock assessment paradigm that drives marine fisheries management in the United States and some other industrialized countries. Stock assessment focuses on estimating a small number of population parameters within targeted fish "stocks" such as number of individuals at age of first reproduction, spawning stock biomass, growth rate, etc. Assuming an inverse correlation between population density and per capita reproductive success, these estimates are used to calculate a stock's "total allowable catch" (TAC). As Spurgeon (1997), Wilson and Degnbol (2002), and Weber (2002) have pointed out, there can be strong pressure on fisheries biologists to provide population estimates that produce the largest possible TACs, which are then used or further increased by fishery managers who are themselves pressured to increase the TAC. The net result of these intense pressures is that the TACs are often unsustainable, as illustrated by the repeated failure of fisheries managed with this process. An illustrative example described by Rieser et al. (2005) concerned summer flounder *Paralichthys dentatus*, an overfished species caught in U.S. Middle Atlantic states that was subject to a rebuilding plan. In 1999, the National Marine Fisheries Service recommended a summer flounder commercial fishing quota so high that the population had only an 18% probability of achieving established population rebuilding goals. Conservation groups sued the federal government for failing to "ensure" population rebuilding. The federal court's decision said, "only in Superman Comics' Bizarro world, where reality is turned upside down, could the Service reasonably conclude that a measure that is at least four times as likely to fail as to succeed" offers confidence that the population will rebuild. Yet, year after year, the National Marine Fisheries Service admits that a sizeable fraction of exploited fish "stocks" are overfished (and that there aren't enough data to determine the status of a far greater number), a success rate orders of magnitude lower than those considered acceptable in other economic sectors subject to federal regulation. Based on statistics for 2003, the National Marine Fisheries Service reported to Congress that of 909 stocks, 138 are not overfished, 76 are overfished, 1 is approaching overfished condition, and 694 are of unknown status or have no defined fishing mortality theshold (NMFS 2004). Thus, 138/855 = 16 % of U.S. fish "stocks" are demonstrably not overfished. In contrast, the established goal of the Federal Aviation Administration for 2004 is to "reduce airline fatal accident rate to 0.028 per 100,000 departures," which means 99.99997% demonstrably will not have fatal accidents (Federal Aviation Administration 2003). An observer might well ask, is the health of our oceans and their fisheries so unimportant that this disparity in standards is acceptable?

Even more interesting than what stock assessments include is what they exclude. Stock assessments treat each fish species as if it exists in isolation from other species, including non-human predators, pathogens and parasites, alternate hosts, prey, competitors, amensals, and mutualists. Moreover, stock assessments do not take into account the intricacies of populations' habitat relations. Yet, early marine fisheries biologists thought about and examined these topics. Mitchell (1918) noted the importance of parasite outbreaks in some fish species. Coker (1938) stated, "Whatever shelter occurs in the sea it is availed of. Clams, worms and crustacea burrow in the bottom, and even in rock, or find concealment among the shells of the bottom…. Oyster beds and thickets of eelgrass harbor a rich and varied population of small plants and animals." And Herrington (1947) voiced concern about effects of bottom trawling on benthic organisms eaten by Georges Bank haddock *Melanogrammus aeglefinus*. It is difficult to fathom how scientific knowledge of such fundamental significance to fisheries could have been downplayed as marine fisheries biology and management narrowed their focus to stock assessment.

In contrast, scientific understanding of ecology in general, and of the ecology of fishes specifically, has broadened and deepened enormously in the last half century. Ecologists, including fish ecologists, have long known that interactions among species are crucial determinants of population levels, age structure, sex ratios, geographic and local distributions, population genetics, reproduction, physiology, behavior, and relationships to habitat in various life history stages. This ecological understanding has become integral to resource management, including wildlife and forest management and even management of freshwater fishes (such as trout). However, ecological understanding appears to have little influence on marine fisheries biology. To test this, I examined *Science Citation Index Expanded* for papers that cite one of the most influential papers in the history of ecology, a study of the keystone role of a predator in shaping a rocky intertidal community (Paine 1966). Of the 500 most recent papers in peer-reviewed journals (published between 1998 and 2004) that cite this seminal paper, only five were in fishery journals. To someone not trained in the canons of marine fisheries biology, the reductionism of its approach, particularly its failure to incorporate the central ideas in ecology, is difficult to comprehend. That would not be a major problem if marine biodiversity and fisheries were in good shape. But serial depletion of targeted species; population crashes of non-targeted species; increasingly convoluted and inconsistent command-and-control regulation of fish "stocks;" management by lawsuits with outcomes dictated by the courts; the unceasing "state of war" between conservationists, fishermen, and fishery managers; and perpetual socioeconomic crises in fishing communities are not signs that the dominant marine fisheries management paradigm is working. An observer of fisheries science and management is forced to the uncomfortable conclusion that the stock assessment paradigm, while potentially useful in very restricted circumstances, is fundamentally flawed. It is time for what Kuhn (1970) called a paradigm shift.

Lessons for Fisheries Biologists from Terrestrial and Freshwater Realms

Some concepts more readily evolve in one realm than another, with good reason. Anyone who has tried to light a fire with wet wood can understand why the field of fire ecology developed in the terrestrial realm, not in aquatic ones. It is scarcely less obvious why disturbance theory developed on land: Humans are better equipped to see the effects of disturbance on land than in the sea. Even those who were not trained as forest biologists (e.g., Norse 1990) readily see how disturbances that change the structure of a terrestrial ecosystem affect species composition and functioning. Seeing these effects is much more difficult in the sea, but absence of evidence is not necessarily evidence of absence. Not having looked, and therefore not having seen these effects in the sea, may well have lulled many to assume that they are not happening.

In truth, very few people—including fishermen or fishery biologists—have spent much time watching what happens on the seabed below depths that scuba divers can reach. Except for the shallowest tens of meters in clear, warm, nearshore seas, the sea is so hostile to humans and so opaque to the unaided human eye that undersea lands are terra incognita. Most of what people know about the seafloor has been learned by blindly dropping sampling gear—such as otter trawls and box cores—that remove organisms from their habitat context and do not tell much about the biology of the specimens we bring up. Imagine for a moment how little we would know about terrestrial ecology if scientists flying in airships above the clouds had to learn about deer and songbirds by extracting their bodies from sampling gear dragged through forests and grasslands!

Understandably, fisheries biology focuses on things its standard sampling tools allow it to estimate—such as the number of eggs—rather than things its tools cannot estimate (including shelter-seeking behaviors of juveniles and social learning of migratory routes). This recalls the wisdom in the saying, "When the only tool you have is a hammer, you tend to treat everything as if it were a nail."

Fortunately, new research tools such as research submersibles, remotely operated vehicles, and side-scan sonar have allowed marine scientists to gain a much better picture of what is happening on the seabed (Figure 2) than was previously available. But improved technology is a double-edged sword. The ability to see the seabed more clearly has also let fishermen locate and catch fish in their last refuges. In effect, new technologies have "turned the sea transparent."

A terrestrial story from the past provides a faultless analogy with the present-day situation in marine fisheries. From the mid-19th century, when it was the most abundant bird in the world, North America's passenger pigeon was eliminated in just one human lifetime. It disappeared because new technologies—particularly telegraphs and railroads—allowed people to reach and kill large numbers and fell the big beech, oak and chestnut trees that were their essential breeding and nursery habitat, thereby disrupting their nesting aggregations (Blockstein 2002). Management efforts seem doomed to fail when officials do not appreciate the effects of improving technologies. The same is true for failure to appreciate basic ecological principles.

One robust principle in ecology concerns the relationship between the spatial complexity of ecosystems and their diversity. More than four decades ago, a terrestrial ecologist and his physicist brother (MacArthur and MacArthur 1961) published a "must-read" study for anyone interested in habitat. It began, "It is common experience that more species of birds breed in a mixed wood than in a field of comparable size." In deciduous forests around the United States, the MacArthurs found that bird species diversity increases with the structural complexity of their habitats. Stimulated by their work, marine geologist Michael Risk (Risk 1972) showed that fish species diversity increases with benthic structural complexity in coral reefs, so marine scientists have known that structural complexity is crucial for species diversity for decades, well before the 1996 revisions of the Magnuson Fishery Conservation and Management Act (FCMA) of 1976. Since the MacArthurs and Risk published these landmark studies, hundreds of scientific papers have examined the relationship between habitat complexity and species diversity on land, in freshwaters, and in the sea.

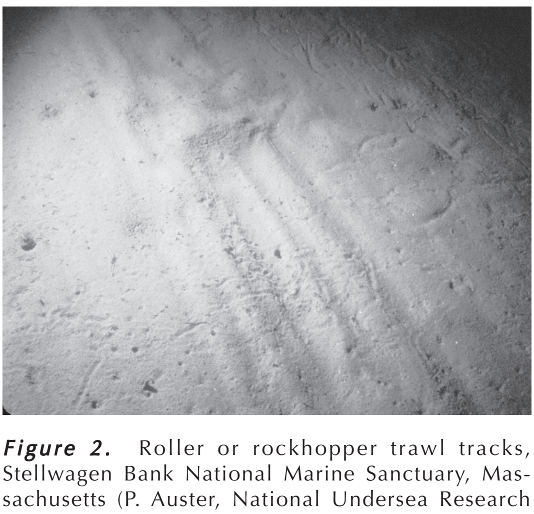

Figure 2. Roller or rockhopper trawl tracks, Stellwagen Bank National Marine Sanctuary, Massachusetts (P. Auster, National Undersea Research Laboratory, University of Connecticut).

As is often the case, such scientific studies merely quantified longstanding common knowledge. In an old African-American folk story called "The Tar Baby," Brer Rabbit is captured by Brer Fox and Brer Bear but tricks them into throwing him into a structurally complex briar patch, allowing Brer Rabbit to escape predation. Most anybody who snorkels or dives has seen fishes avoid approaching humans by hiding in the interstices of a reef. And most freshwater recreational fisherman know that the best fishing spots for trout and black bass *Micropteris* spp. are among tree roots beneath undercut banks, among branches of sunken trees, and in submerged vegetation. The importance of structural complexity is widely understood—by managers and the public alike—to be vital on land and in freshwaters. There is an abundance of scientific studies in fisheries journals such as the *North American Journal of Fisheries Management* on the importance of complex structures in streams and lakes. Yet, even a diligent search through the leading fisheries journals will show that fisheries management has largely overlooked the importance of structural complexity in the sea.

Seafloor Structures

People in vessels on the sea's wavy, reflective surface can be deceived into thinking mainly about the water column, the pelagic realm, which appears almost structureless to the naked eye. The dominant marine fishery management paradigm seems to overlook the fact that more than 98% of marine species live in, on, or immediately above the seabed (Thurman and Burton 2001). Their morphological, physiological, and behavioral adaptations are for living in, on, or just above the seabed. They settle there, extract oxygen from its waters, feed on other members of benthic communities, find shelter from predators, grow and reproduce in, on, or just above the seabed. Hence, the relationship of marine species to their benthic habitat is of paramount importance to understanding the biology of marine life. Failure to apply this understanding contributes to problems associated with the present fisheries management paradigm.

It is important to note that not all benthic species need seafloor structures. Hence, some larger fish and invertebrate species occur on flat, "seemingly" featureless bottoms that may have naturally short disturbance return intervals. By and large, these species—including surf clams *Spisula solidissima*; many penaeid shrimps; raninid crabs; portunid crabs in the genera *Ovalipes*, *Arenaeus*, and *Callinectes*; angel sharks *Squatina* spp.; most dasyatid stingrays; lizardfishes (synodontids); and soles (soleids)—are cryptically colored and/or can quickly bury themselves in the sediment, attributes that allow them to reduce risk of predation.

However, a disproportionately large number of benthic fish and shellfish species are closely associated with geological or biological seafloor structures. A key experimental study by Lindholm et al. (1999) illustrates one reason this seems to be so. It shows that juvenile Atlantic cod *Gadus morhua* are more successful at escaping predators in more complex habitats. But because benthic diversity and biomass are so much greater than in the water column, the seafloor also offers many more feeding opportunities for predators.

As Norse and Watling (1999), Auster and Langton (1999), the National Research Council (2002), and others have shown, dragging heavy trawls and dredges across the seafloor rolls boulders; planes high spots; homogenizes sediments; and crushes, buries, and exposes to scavengers wildlife living in and on the seafloor. Figures 3–8 show the dramatic contrast between untrawled and trawled seafloors in three widely separated areas of the world. Until the 1980s in the United States, fishermen considered rough bottoms too dangerous to trawl, but introduction of roller and rockhopper groundgears have allowed fishermen to trawl on bottoms they had previously avoided.

Figure 3. Untrawled glass sponge reef, Hecate Strait, British Columbia (M. Krautter, Institut fuer Geologie und Palaeontologie, Universitaet Hannover).

Figure 4. Trawled glass sponge reef, Hecate Strait, British Columbia. Note trawl track (M. Krautter, Institut fuer Geologie und Palaeontologie, Universitaet Hannover).

Figure 5. Untrawled gorgonian-sponge forest, Northwest Australian shelf (K. Sainsbury, Commonwealth Science and Industry Research Organization)

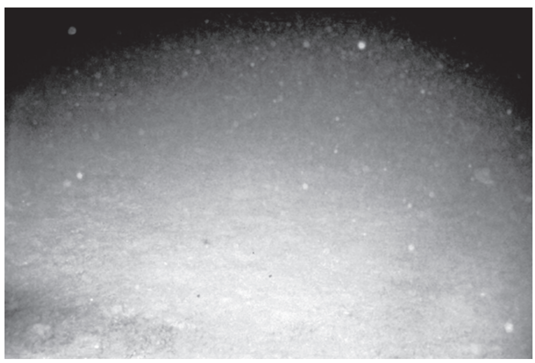

Figure 6. Trawled gorgonian-sponge forest, Northwest Australian shelf (K. Sainsbury, Commonwealth Science and Industry Research Organization)

Figure 7. Untrawled *Oculina* coral reef with gag *Mycteroperca microlepis* and scamp *M. phenax*, Oculina Bank, Florida Atlantic Coast (R. Grant Gilmore, Dynamac Corporation).

The impacts of trawling and dredging are remarkably similar to more familiar terrestrial forms of disturbance such as clear-cutting (Watling and Norse 1998) and chaining, a process for clearing terrestrial vegetation in which a chain is stretched between two bulldozers. Differences, however, include the vastly greater area of the Earth that is trawled and dredged (often repeatedly), the fact that fishing with mobile gear happens out of sight, the generally smaller size of seafloor structure-forming species, the greater vulnerability to disturbance of deepsea ecosystems compared with most forests, and the near absence of effective fish habitat protection even 9 years after the FCMA was amended to require protection of essential fish habitat.

Figure 8. Trawled *Oculina* coral reef, Oculina Bank Habitat Area of Particular Concern, Florida Atlantic Coast (L. Horn, National Undersea Research Center, University of North Carolina at Wilmington).

Many fish species of special conservation concern (e.g., Atlantic cod, Nassau grouper *Epinephelus striatus*, gag *Mycteroperca microlepis*, lingcod *Ophiodon elongatus*, bocaccio *Sebastes paucispinis*, yelloweye rockfish *S. ruberrimus*, and darkblotched rockfish *S. crameri*) live in close association with structurally complex seafloor habitats. Undoubtedly, overfishing has contributed substantially to their decline, but both logic and evidence indicate that human-caused disturbance of their habitat from trawling has also contributed substantially to their population decline and failure to recover. The disappearance of these demersal species leads to the conclusion that marine fisheries management needs to advance conceptually and operationally, as have other living resource management paradigms, beyond simply attempting to control human-caused mortality to protecting and managing species within their habitats or—still more broadly—to doing so while maintaining key ecosystem processes.

There is growing concern in the scientific community about loss of benthic structure-formers, including seagrasses, ascidians, bryozoans, tubiculous amphipods, tubiculous polychaetes, tubiculous anemones, pennatulaceans, and—most prominently—corals and sponges. On February 15, 2004, at the annual meeting of the American Association for the Advancement of Science in Seattle, Washington, 1,136 conservation biologists and marine scientists from 69 countries issued an unprecedented Scientists' Statement on Protecting the World's Deep-sea

Coral and Sponge Ecosystems (Marine Conservation Biology Institute 2004). The statement says that these structure-forming species need to be protected, identifies bottom trawling as the greatest threat to them, and calls for a moratorium on bottom trawling on the High Seas, a ban on bottom trawling within nations' exclusive economic zones where these structurally complex communities are known to occur, prohibition of roller and rockhopper trawling groundgear, research and mapping of deep-sea coral and sponge communities, and establishment of protected areas to conserve these communities.

Areas of seafloor that have been trawled heavily undergo major shifts in species composition, just as clearcut areas do on land. Reports from a seminal study on the northwestern Australian shelf before and after trawling was initiated (Sainsbury 1987, 1988) showed that removing structure-forming gorgonians and sponges from soft bottoms (Figures 7, 8) changes fish species composition from disturbance-intolerant, commercially high-value species for which benthic structure is important, such as groupers (serranids), snappers (lutjanids) and emperors (lethrinids), to low-value lizardfishes (synodontids) and threadfin bream (nemipterids), which apparently do well on disturbed, flat, seemingly featureless bottoms. There is an intriguing suggestion in the scientific literature (e.g., Engel and Kvitek 1998) that some flatfishes do well on heavily trawled bottoms, perhaps because frequent disturbance increases their preferred foods. Similar patterns have been seen in Alaska and the North Sea. For instance, the Groundfish Forum, an Alaska-focused trawling industry group, says, "flatfish populations are known to be growing very large in proportion to other groundfish and shellfish populations" (see Issues and Initiatives section of *www.groundfishforum.org*).

In forests, the dramatic change in an ecosystem's dominant species composition is called "type conversion." Under the National Forest Management Act, the U.S. Forest Service must "provide, where appropriate, to the degree practicable, for steps to be taken to preserve the diversity of tree species similar to that existing in the region controlled by the plan." Thus, the U.S. Forest Service—an agency that has long been criticized for favoring resource exploitation over biodiversity protection—nonetheless strongly discourages type conversion on our public lands. In contrast, the U.S. National Marine Fisheries Service allows the commercial fishing industry to cause profound ecosystem shifts on undersea public lands. The FCMA as amended in 1996 requires the National Marine Fisheries Service to consider cumulative effects of fishing. The growing number of lawsuits by conservation organizations (which is approximately the same as the number filed by fishing interests, according to public comments by Eric Bilsky (Oceana, Washington, D.C.) reflects the belief that the National Marine Fisheries Service is not meeting its public trust responsibilities, including those concerning cumulative impacts of fishing. Fisheries managers cannot succeed in meeting public trust responsibilities without restricting or eliminating type conversion of seafloor ecosystems.

Shifting to an Ecosystem-Based Management Paradigm

Leading thinkers in forestry, most notably Jerry Forest Franklin, catalyzed a management paradigm shift in the 1980s by showing the need to maintain structural complexity in the ecosystems with which forest managers were entrusted. Ecosystem management—or, more appropriately, ecosystem-based management (because what we manage is human activities that affect ecosystems)—has rapidly become the new paradigm in forest management (Agee and Johnson 1988; Kohm and Franklin 1997). Franklin (1989) called upon his colleagues to embrace a new, more encompassing way of thinking in saying, "Forestry needs to expand its focus beyond wood production to the perpetuation of diverse forest ecosystems." Growing numbers of managers now accept that forests are about more than producing wood. But, for fisheries managers wedded to the stock-assessment paradigm, marine ecosystems have been about producing meat. At least one marine management regime (Convention on the Conservation of Antarctic Marine Living Resources) has embodied ecosystem-based management since the 1970s, and the most forward-thinking elements of the marine community are increasingly calling for ecosystem-based management (National Research Council 1999; Pew Oceans Commission 2003), but thinking and practice in marine resource management lag behind forest resource management.

It is not too late for fishery biologists and managers to embrace this paradigm shift**.** A growing number of fisheries biologists are ready to follow their terrestrial counterparts and the urgings of other marine scientists and policy experts in adopting ecosystem-based management. Note that I am not using the term "fisheries ecosystem management" here. Fisheries are just one subset of humans' broader interest in maintaining and recovering the sea's biodiversity. They are a crucial part of the mix, no doubt, but they are not everything.

I would like to offer legislators, managers, and my fellow scientists a new goal and five robust principles that I believe can benefit virtually everyone who catches fish, eats them, watches them, or merely wants to know that they exist. The goal of ecosystem-based management in the sea is to maintain biodiversity and fisheries by protecting and recovering ecosystem composition, structure, and function. From this goal comes five principles:

(1) Stop destructive fishing methods, overfishing, and all other preventable threats. It is essential to stop treating fish populations as if failing to meet management objectives is unimportant and as if quantity and quality of their habitats don't matter.

(2) Allow populations and ecosystems to recover or, where necessary (e.g., Lenihan and Peterson 1998), intervene actively to recover the geological and biological habitat structure that undergirds their species composition and functioning.

(3) Establish comprehensive ocean zoning that fully protects a sizeable fraction of all marine ecosystems and allows sustainable fishing in other zones.

(4) Err on the side of caution; put the resource first. We must use the precautionary approach. As a wise fish biologist and friend says, "No fish, no fishing."

(5) Fully involve fishermen and conservationists in shaping sustainable solutions. We need the wisdom of fishermen as well as the objectivity of public-interest conservationists who do not profit financially from catching fish but who have long-term interests in sustainable ecosystems for their own sake and the benefit of all people, including fishermen.

As the 146 years since the publication of Darwin's The Origin of Species have shown, the idea of evolution worries people who desperately want to cling to what is familiar and constant. Change is frightening. As Samuel Clemens (Mark Twain) noted, "Denial ain't just a river in Egypt." We cannot deny that our evolving technologies have increased our fishing capacity to the point where increasing numbers of fish species are facing ecological, commercial, and perhaps even biological extinction. Therefore, it is incumbent upon fisheries biologists, other marine scientists, conservation advocates, and people entrusted with making decisions to evolve how we manage marine ecosystems to maintain their marine biological diversity and fisheries for our lifetimes and for future generations of both marine life and people.

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