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Biodiversity, Function, and Interconnectedness: A Revolution in Our Understanding of Marine Ecosystems and Ocean Conservation

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We can be ethical only in relation to something we can see, feel and understand, love or otherwise have faith in.
—Aldo Leopold, *A Sand County Almanac*

Over the past several decades, technology and interdisciplinary research have led to a vast expansion of our understanding of the diversity of life in the ocean, the importance of the ocean to life on Earth, and the interconnectedness between terrestrial and marine ecosystems. With this new knowledge and several critical new paradigms, we are better able to understand the ocean, manage fisheries, restore ecological functions, and respond to the challenges to the ocean that lie ahead.

3.1. THE PAST: A DISCONNECTED, MYSTERIOUS, BOUNDLESS OCEAN

In the Age of Exploration, voyagers set forth from Portugal in the early fifteenth century to find new lands and new routes of trade. Two hundred years later, navigators sailed competently along these routes throughout the world (Cooke 1712/1969). So, it is remarkable that today 90 percent of the ocean still remains to be explored. New marine species are still discovered regularly, even entirely new mechanisms for life. One the most important scientific discoveries for marine biodiversity occurred late last century, in 1977, when the submersible *Alvin* encountered chemosynthetic life forms at a hydrothermal vent on the deep seafloor for the first time (figure 3.1). This discovery literally changed our understanding of what's possible for life on Earth.

In more recent decades, our collective understanding of the ocean has shifted in both drastic and subtle ways, while our appreciation of the consequences of the human footprint on the marine environment has deepened (Halpern et al. 2008). The ocean was once described as a mosaic of adjacent but discrete habitats. The deep sea was characterized in the mid-19th century by Edward Forbes as an "azoic zone" (Gage and Tyler 1991) abounding with mysterious, deep, dark, and supposedly barren regions. The shallow coastal waters were the opposite, teeming with an inexhaustible abundance of life. The ocean seemed such a great expanse that it was deemed ever ready to absorb our flowing streams of waste. This fertile, unfamiliar, and forgiving expanse was the ocean of all previous recorded history (Patton 2006).

The ocean we know today is complex and interconnected (Church 2007). Transoceanic migrations of animals (figure 3.2) and people bring distant shores closer together with shared habitats, species, enterprises, and resources. Today's ocean is far less mysterious than the one of Forbes's era, yet many mysteries remain to be solved. Coral reefs are one

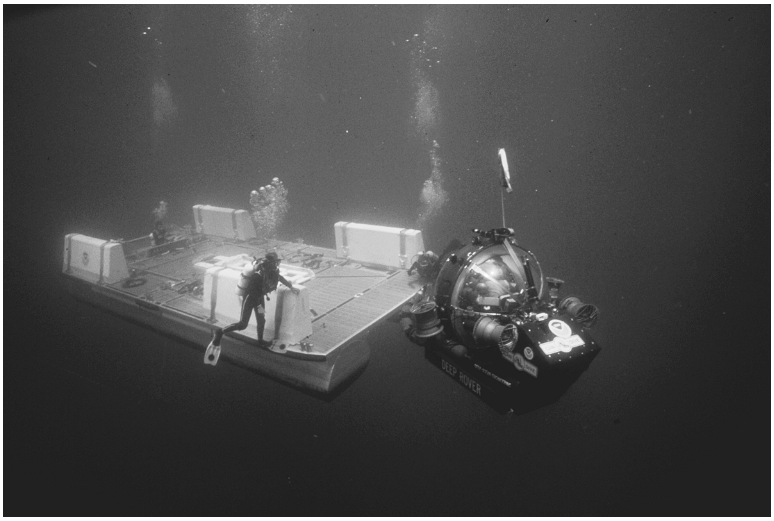

FIGURE 3.1 *Deep Rover* submersible. (Courtesy of OAR/National Undersea Research Program/Univ.of Hawaii)

of the most biologically diverse ecosystems on the planet, but new reef species continue to be discovered at an exponential rate. Species accumulation curves for fish (Mora et al. 2008), crustaceans (Martin and Davis 2006), and corals (Cairns 2007) exhibit no sign of an asymptote (figure 3.3). Even in well-known groups such as fishes, one in five species remains to be discovered (Mora et al. 2008). Discovery rates are high, but at the same time, commercial fisheries are collapsing worldwide. It seems a paradox—the ocean remains a boundless source of novelty and resilience, but ocean resources are dwindling and are clearly exhaustible. The modern ocean can be characterized as abundant in life, within a framework of limited resources in a highly variable climate affected by clear anthropogenic insults linked to ecosystem function.

What we have taken out and put into the ocean, combined with our ability to reengineer coastal waters and lands, has resulted in a transformation of marine ecosystems on a global scale (Gibbs 2000; Schlacher et al. 2007). Many fisheries are at or beyond capacity, target species are largely extirpated, and bycatch endangers nontarget species (Jackson et al. 2001). In many places the ocean has reached its capacity to break down our waste, or the composition of our waste, in the form of plastics and man-made chemicals, has overridden its natural assimilative abilities. Development and increasing population pressures, intensive aquaculture, and bottom trawling have flattened or destroyed marine ecosystems, particularly near the coast. In the United States, 79 percent of coastal resources are classified as threatened or impaired (U.S. EPA 2005). The human fingerprint can be detected in virtually every corner of the world ocean (Halpern et al. 2008).

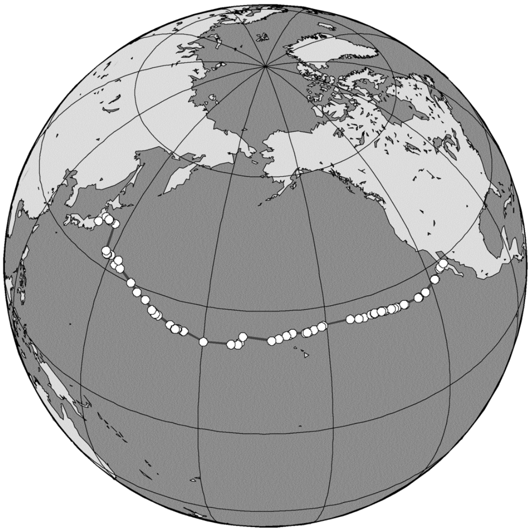

FIGURE 3.2 First transoceanic satellite tracking of a sea turtle (*Caretta caretta,* 368 days, ~12,000 km), 1996–1997. (Data from Nichols et al. 2000)

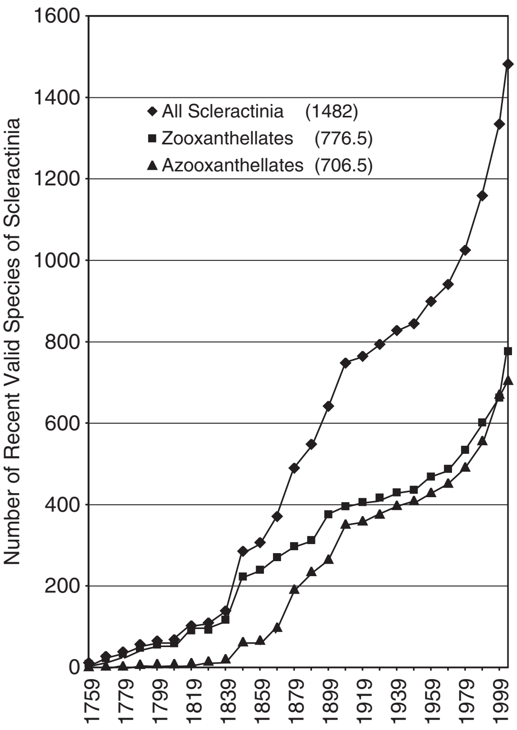

FIGURE 3.3 Cumulative number of recognized (valid) zooxanthellate, azooxanthellate, and total scleractinian species from 1759 through 2004. (Reprinted with permission from Cairns 2007)

Briggs (1974) described the greatest marine obstacle to the dispersal of shallow-water organisms—5,400 km of uninterrupted deep water between the central and eastern Pacific he called the Eastern Pacific Barrier (EPB). We now know that animals regularly migrate and disperse across entire ocean basins and that numerous species are now shared on both sides of the EPB. These "transpacific" species are considered evidence of invasions through the barrier. Though the EPB is an important obstacle to dispersal for some taxa, gene flow does occur across the barrier (Lessios et al. 1998). A growing list of fish and marine megafauna, including sharks, sea turtles, billfish, sea birds, and marine mammals, have been found to utilize vast areas, often entire ocean basins, and multiple ecosystems during their developmental and reproductive migrations (Hodgson et al. 2006; Nichols et al. 2000; Shaffer et al. 2006; Shillinger et al. 2008).

Past accounts of fish and megavertebrate abundance (Jackson et al. 2001) are rife with depictions of "men walking across their backs," "pushing the bow through their schools," and "scooping them into the boat with buckets." Whether spawning salmon, foraging sea turtles, or aggregating cod, the stories were the same (Aiken et al. 2001). Our perception that this bounty was endless, bottomless, and resilient is understandable. Until a century ago, our ability to access these resources was limited, as our range was short and our fishing gear was primitive. But our skill at catching these animals, the demand for their oil, flesh, and skin, and the technology used to find them soon outpaced our understanding of their capacity to regenerate (Roman and Palumbi 2003). Worsened by degradation of their habitat, the result has been ecological and commercial extinction for many species and a global rescue effort involving scientists, governments, citizen groups, and businesses. Endemic species, such as the totoaba in Mexico's Gulf of California (Cisneros-Mata et al. 1995), have been fished to ecological extinction (figure 3.4).

FIGURE 3.4 Fishers hauling in a catch of totoaba (*Totoaba macdonaldi*) along the shores of the Gulf of California in 1937. Endemic species such as the totoaba have been fished to ecological extinction in many areas worldwide. (Photo courtesy of J. Seminoff)

FIGURE 3.5 Transformation of coastal habitat via accumulation of plastic debris on a beach in the Philippines. (Photo courtesy International Coastal Cleanup)

Furthermore, there's no doubt that most every edible species in the ocean was once far more abundant in number and larger in size (Pauly 1995). We are now aware that the cost of this miscalculation and ignorance has been the loss of ecological, social, cultural, and economic capital on a global scale (Costanza 1999).

For most of human history, societies operated as if the ocean could assimilate all of our waste, washing it away. "Dilution is the solution for pollution" was the mantra, and the ocean eventually became the ultimate downstream recipient, or sink, for all liquid, solid, chemical, and biological effluent. The ancient Greeks believed and Euripedes wrote that "the sea can wash away all evils." A wide range of cultures adhered to the belief that the sea makes life on land possible by making it "pure" (Patton 2006).

Until the birth and rise of the modern petroeconomy over the past century, the strategy of "cleansing by the sea" was mostly successful. But proliferation of petroleum-based fuels (e.g., gasoline, kerosene, liquefied natural gas, and fuel oil), plastics (including precursors benzene, ethylene, propylene, toluene, and mixed xylenes), and other products (asphalt, tar, paraffin, and lubricating oils) has overwhelmed the ocean's capacity for biodegradation, inflicted a wave of new, deadly threats to marine life, and transformed life in many parts of the sea (figure 3.5). These include spills, ingestion, entanglement, dead zones, disease, and climate change. Petrochemicals and fuels, in their current form and at present scales, are not compatible with life in the ocean. Accumulation of these substances over the past century is harming the health of the ocean and ocean-based commerce in ways we are only beginning to understand (Sheavly and Register 2007).

3.2. THE NEW TOOLS

In the last few decades, submersible and satellite technologies have developed to the point where we stand at the threshold of a new modern age of ocean awareness. Space-borne satellites transmit global sea surface temperature, ocean color, and sea surface-height data in such volumes that the only observable limit to our understanding is manpower (Ducet et al. 2000). Hurricanes can be detected and their trajectories projected for weeks in advance of a storm's landfall. Autonomous vehicles can map the seafloor and the water column. Drifting instruments can map the plankton and the ocean currents. Coordinated international programs help to organize and evaluate this information. New technologies such as these can open the doors of scientific discovery, but at the same time they place the sea in jeopardy.

Commercial fisheries now rely on satellite and sonar data (Etnoyer et al. 2004), and they are fishing deeper than ever before (Roberts 2002), so fish have fewer places to hide. Our ocean resources were once considered inexhaustible, but the data indicate most populations are in decline (Myers and Worm 2003; Worm et al. 2005), the average size of tuna is decreasing (Golet et al. 2007), and humans are fishing down the food chain (Pauly et al. 1998; Myers et al. 2007). The largest animals have already gone to market. Global demand for seafood is also driving habitat destruction on a monumental scale. Mangroves are converted to shrimp farms (Barbier 2000; Barbier and Cox 2004), deep-sea coral beds are flattened by bottom trawlers (Roberts 2002; Watling and Norse 1998), and coral reefs are decimated by bomb fishing and are shifting to algae as herbivores are extirpated from these ecosystems (Hughes 1994; McManus and Polsenberg 2004). It is sobering to think that unknown species of animals may be lost to these fisheries before they have been discovered (Jones et al. 2004).

Pelagic ocean animals such as tunas, sharks, sea turtles, and marine mammals have historically been difficult to study due to their vast movements and large body size. The development of small microprocessor-based data storage tags that are attached, implanted, or satellite-linked provide a novel way to study the animals' movements, behavior, and physiology in the wild (Block 2005). When data acquired from tags are combined with remotely accessed deep-sea data, satellite-derived sea surface temperature, and ocean color data, the relationships among movements, behaviors, and physical ocean environment can be examined. Furthermore, animals carrying tags act as oceanographic sensors providing data wherever their dives and migrations take them (Block et al. 2005; Fedak 2004). This "biologging" science is providing new insights into movements, habitat use, reproductive behaviors, and population structures of marine animals. The data also describe migration corridors, hot spots, and physical oceanographic patterns that are important to understanding how organisms such as loggerhead and leatherback turtles (Benson et al. 2007; Etnoyer et al. 2006; Godley et al. 2008; Peckham et al. 2007; Shillinger et al. 2008) use and connect open ocean and coastal environments (figures 3.6 and 3.7).

Understanding the factors influencing animal movements and ocean health on large geographic

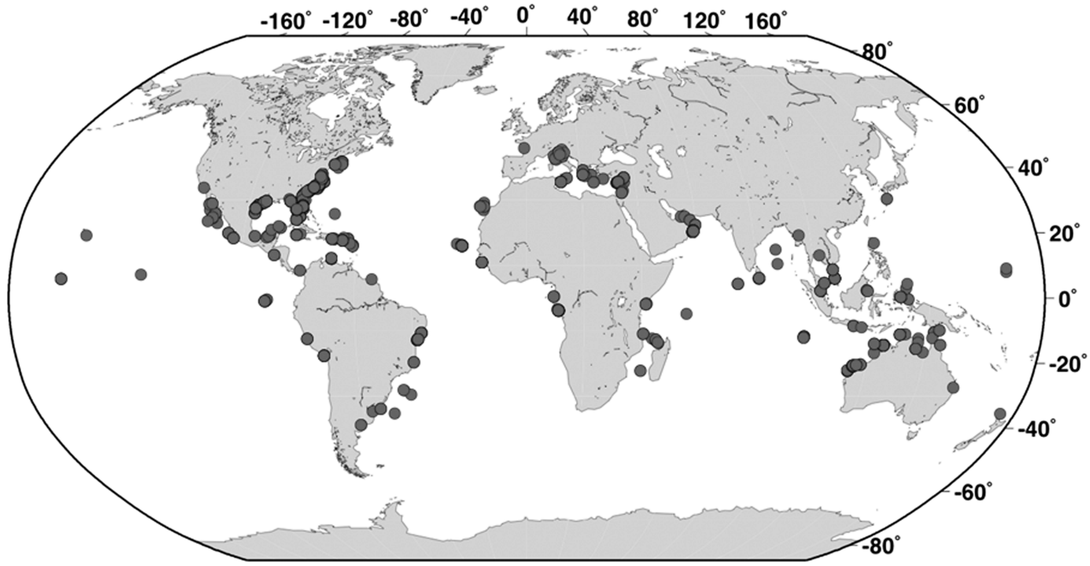

FIGURE 3.6 Spatial footprint of STAT (Satellite Tracking and Analysis Tool; see Coyne and Godley 2005) turtle-tracking projects. Circles denote the launch point of marine turtle tracking with data managed within the STAT system. (Data from Godley et al. 2008)

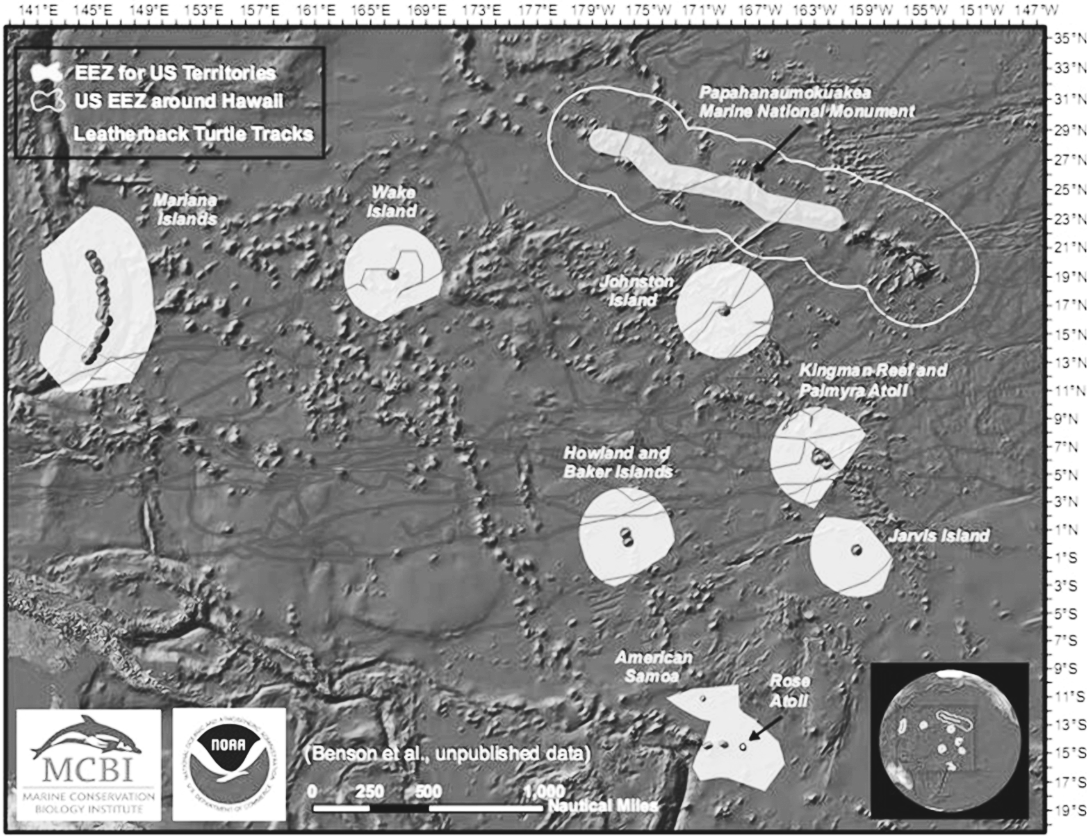

FIGURE 3.7 Leatherback turtle tracks passing through the exclusive economic zones for U.S. territories, Hawaii, and the Papahanaumokuakea National Monument. (Data from Benson et al. 2007, unpublished data)

scales is often intractable, as is learning the broad-scale impacts from anthropogenic actions. In recent decades, and especially in the last five years, use of remotely sensed (i.e., satellite-derived) ocean data has increased. This has been made possible through more user-friendly dissemination tools (see NASA's PO.DAAC OceanESIP Tool [POET] and NOAA's Coastwatch; D. Foley, personal communication), and a greater commitment on the part of data users to integrate various data sets to gain a better understanding of ocean processes. For example, the oceanic movements of a variety of marine mega-vertebrates such as sea turtles, large migratory fishes, and marine mammals have been increasingly tracked through satellite telemetry, and these tracks have been integrated with a variety of ocean data (Etnoyer et al. 2004, 2006; Kobayashi et al. 2008; Polovina et al. 2006).

Basic environmental features such as bathymetry, surface currents, sea surface temperature, sea surface height, chlorophyll, and primary productivity have been standard products from satellites for decades, but only recently have these ocean data sets been used to describe the mechanisms underlying animal movements and habitat use. For example, dynamic mesoscale processes such as sea surface temperature and chlorophyll fronts—areas of interface between two dissimilar water masses—are known to strongly affect water column primary and secondary productivity (Olson et al. 1994; Palacios et al. 2006), and their status as prey aggregation zones indicates they provide food and thus influence movements of large marine organisms such as large whales (Doniol-Valcroze et al. 2007), sea turtles (Kobayashi et al. 2008; Polovina et al. 2006; Seminoff et al. 2008), and commercially targeted species such as tuna and swordfish (Fiedler and Bernard 1987; Podesta et al. 1993).

Biologists are only beginning to grasp the full potential for the integration of shared biological and oceanographic data through open distribution networks, but oceanographers have been using these tools for decades (Poiani et al. 2000; Tsontos and Kiefer 2002). This is due partly to the representative scale of their investigations. Physical oceanographers require data across broad geographic scales to forecast hemispheric and basin scale phenomena like El Niño–La Niña Southern Oscillation. Beginning with archives of ship drift data, the historical data management scheme was a broad network of data acquisition, in recent times using shared instrumentation such as the TAO/TRITON array of equatorial buoys funded by international cooperation. Twentieth-century biologists have had less incentive to cooperate. Biologists are also more accustomed to working at the scale of a coral reef, estuary, or rocky shore. They generally work alone or in small groups. But the scale of interest is now beginning to overlap between these disciplines. Biologists are "scaling up" their studies to the extent of species migrations, while oceanographers seek finer resolution in thermohaline structure, for example, and other oceanographic phenomena. A middle ground is emerging. Advances in computing power, communications, and ship-borne and satellite remote sensing have made the dissemination of animal tracking and oceanographic data easier, more cooperative, and more accessible to everyone.

3.3. DESCRIPTION OF MAJOR OCEAN ECOSYSTEMS

An ecosystem is a functional unit comprising all the organisms in a particular place interacting with one another and with their environment, interconnected by an ongoing flow of energy and a cycling of materials. It includes the physical and climactic features and all the living and dead organisms in an area that are interrelated in the transfer of energy and material functioning. As an ecological unit in nature, this definition of ecosystem requires assumptions of energetics, ecological interactions, and species adaptations.

However, strictly defining an ecosystem can be challenging on land, and perhaps more so in the ocean. The hallmark of ecology is its encompassing and synthetic view of nature, rather than a fragmented view (Odum 1977).

Marine ecosystems are a part of the largest aquatic system on the planet, covering more than 70 percent of Earth's surface. Extending from the deep, open ocean, landward the major ocean ecosystems include the oceanic (deep sea), neritic (open waters), high-energy (intertidal), low-energy (mangroves, marshes, and estuaries) and supratidal (beach strand zone) systems.

There are many different ways of describing ocean ecosystems. They may be defined by size: the whole ocean may be regarded as one giant ecosystem. On a smaller scale, separating the coasts and oceans into 64 large marine ecosystems, 200,000 or more square kilometers and associated with 95 percent of the fish and shellfish yield of the world, has been useful in the global effort to better manage the ocean (figure 3.8; Duda and Sherman 2002). On an even smaller scale, vegetation units such as an individual mangrove forest ecosystem would be in the range of $10\,m^2$ to $100\,km^2$.

A primary producer such as sea grass, kelp, mangrove, or coral reef frequently defines ocean ecosystems. The boundaries of these systems are taken as the boundaries of the vegetation type. Ecosystems may also be defined by geographical and geological boundaries such as wet coastal, intertidal and littoral, estuaries and enclosed seas, coral reefs, continental shelves, and deep ocean.

Marine ecosystems are important to the overall health of both marine and terrestrial environments. Coastal systems alone account for approximately one-third of all marine biological productivity. Estuarine ecosystems (i.e., salt marshes, sea grasses, mangrove forests) are some of the most productive regions on the planet. Marine ecosystems such as coral reefs host some of the highest levels of marine diversity in the world.

The diversity and productivity of the ocean are also critical to human survival and well-being. These ecosystems provide us with a rich source of food and income and support species that serve as animal feed, fertilizers for crops, additives in foods, and a wide diversity of consumer cosmetics. Mangroves, reefs, and sea grass beds provide protection to coastlines by reducing wave action and helping to prevent erosion, while areas such as salt marshes and estuaries have acted as sediment sinks, filtering runoff from the land (Kathiresan and Narayanasamy 2005).

Whichever scheme is used to define marine ecosystems, they are all connected by the common

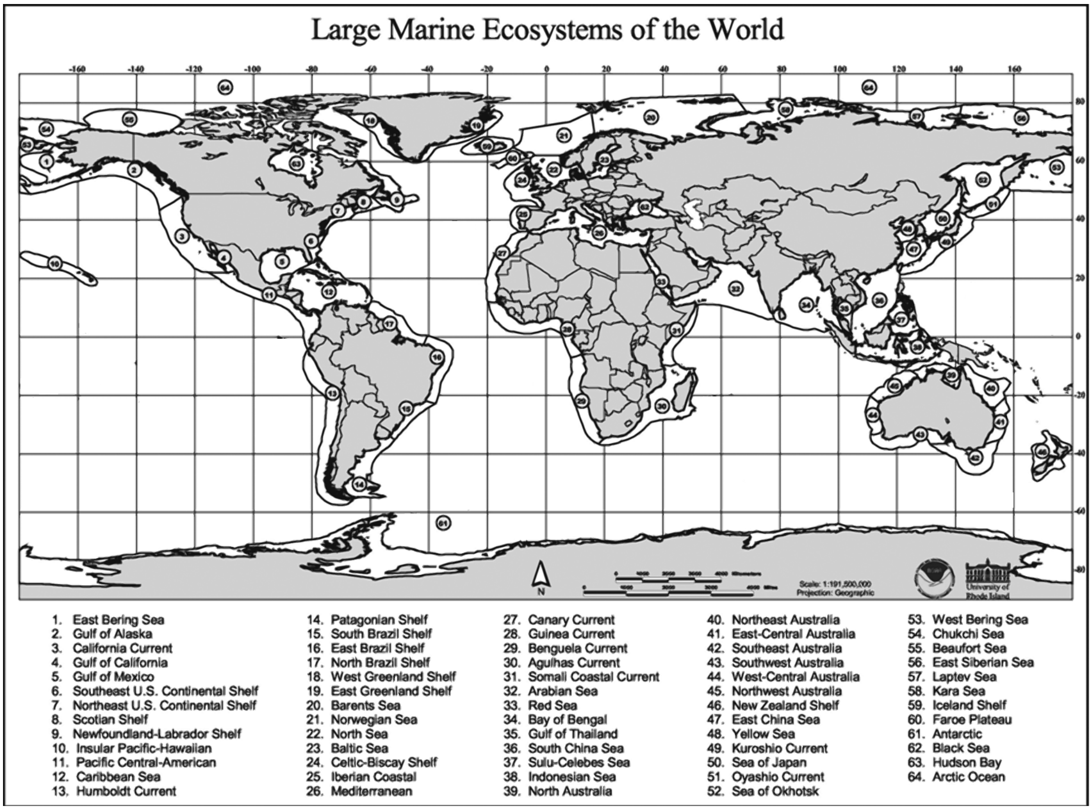

FIGURE 3.8 Large marine ecosystems are areas of the ocean characterized by distinct bathymetry, hydrography, productivity, and trophic interactions. They annually produce 95 percent of the world's fish catch. They are national and regional focal areas of a global effort to reduce the degradation of linked watersheds, marine resources, and coastal environments from pollution, habitat loss, and overfishing. (Courtesy of National Oceanic and Atmospheric Administration)

medium of seawater. This dynamic interconnectedness has driven the evolution of life in the ocean and in more recent times has led to its decline.

A combination of shipping, platforms, canals, aquaculture, fisheries, and climate change has resulted in a breakdown of the natural barriers in the sea, increasing numbers of introduced species and a profound alteration of the structure, composition, and function of marine ecosystems. Ships and platforms in particular provide settlement substrate to pelagic larvae that would have otherwise met their limits of dispersal. This allows exogenous species to invade new habitats, and the species become predominant because their natural predators are absent (Heithaus et al. 2008). Despite the importance of marine systems to our life and economy, increased human activities such as overfishing, coastal development, pollution, and the introduction of exotic species have caused significant damage and pose a serious threat to marine biodiversity and the global ocean ecosystem.

3.4. THREATS TO OCEAN ECOSYSTEMS

Despite the expansion of technology and the revolution in our understanding of the sea, threats to ocean ecosystems remain and must be addressed accordingly. A summary of threats, organized into three main groupings along with representative examples, follows.

Too Much In: The term represents ocean pollution in its various forms. Pollution enters the marine environment as chemicals, runoff, oil spills, noise, debris, heat, sewage, effluent, and pesticides, among others. As the number and volume of these substances increase, the ocean's ability to assimilate them has been overrun, the symptoms of decreased ocean health have become more obvious, impacts on some ocean ecosystems have reached irreversible stages, and negative impacts to human health are increasingly clear (Aguirre et al. 2006; Domingo et al. 2006; Fleming et al. 2006; Jackson 2008; Mozaffarian and Rimm 2006).

Unlike the obvious and highly visible effects caused by oil and debris, some chemicals have invisible but long-term and far-reaching effects on the marine ecosystem. They can be persistent, transported great distances, pass easily through barriers, and accumulate in the marine food chain from prey to predators to humans (DeWailly and Knap 2006). The behavior and effects of persistent pollutants on marine animals (invertebrates, vertebrates, fish, mammals, reptiles, and birds) and people are receiving increased attention (Fleming et al. 2006).

For example, increasing incidence of exposure to heavy metals and other contaminants in the marine environment is of serious concern. Contaminants such as PCBs, mercury, copper, and other metals have been found in tissues of a variety of marine species from numerous areas (Lewis 2006). Although their explicit effects on marine flora and fauna have yet to be determined, such exposure may lead to immunosuppression or other hormonal imbalances (J. Keller, personal communication, 2006). Many of these agents also diminish the health of coastal marine ecosystems, which may in turn adversely affect the species that inhabit these areas.

Researchers have long suspected that runoff of fertilizer from big farms can trigger sudden explosions of marine algae capable of disrupting ocean ecosystems and even producing "dead zones" in the sea. A study by Beman et al. (2005) presented the first direct evidence linking large-scale coastal farming to massive algal blooms in the ocean. This agriculture-to-ocean impact is an increasingly common occurrence around the world and is a key stressor on ocean ecosystems, with dead zones reported from more than 400 systems, affecting an area of more than 245,000 square kilometers (Diaz and Rosenberg 2008).

Marine debris, especially in the form of plastics, is one of the most widespread pollution problems facing the world's oceans (figure 3.5). Nets, food wrappers, cigarette filters, bottles, resin pellets, and other debris items can have serious impacts on wildlife, habitat, and human safety (Sheavly and Register 2007). Marine debris can lead to injury and mortality and reduce food intake and digestive capacity of marine animals (Bugoni et al. 2001). Successful management of the problem requires a full understanding of both marine debris, toxicology as well as animal and human behavior. Education programs, strong, progressive laws and policies, and governmental and private enforcement are needed for a successful marine pollution prevention initiative. Industry also has a role to play in searching for technological mitigation strategies and engineering of bioplastics and systems to reduce waste altogether.

Too Much Out: This term encompasses overfishing, overhunting, and bycatch. The grim reality is that even if pollution in the seas were eliminated, the rate of extraction from the sea would remain at a devastating level. Overfishing occurs in artisanal and industrial fisheries and includes illegal hunting of megavertebrates such as sea turtles and sharks as well as widespread piracy (Berkes et al. 2006; Heithaus et al. 2008). Commercial algae harvesting operations also threaten the integrity of coastal habitats (Pacheco-Ruiz and Zertuche-Gonzalez 1996).

Fisheries bycatch in artisanal and industrial fishing gear has a major impact on large, slow-growing species such as marine mammals and sea turtles (Crouse 2000) as well as sea birds, fish, and invertebrates (Pauly 2007; Peckham et al. 2007). The fisheries responsible include those using drift nets, long-lines, set nets, pound nets, and trawl gear. Their adverse impacts on sea turtles have been documented in marine environments throughout the world (National Research Council 1990). Bottom trawling, the preferred gear used by shrimpers around the world, is perhaps the least efficient and most destructive (figure 3.9; Harrington et al. 2005; Watling and Norse 1998).

Although the full impact from these ongoing and proposed human activities is difficult to quantify, the burgeoning fleets around the world and pending human population expansion is reason for major concern. For example, the removal of top predators appears to have greater ecological impacts than previously understood (Heithaus et al. 2008).

Destroying the Edge: This term describes human population, habitat conversion, coastal development, and mining/dredging. In addition to the intentional exploitation of marine species, a variety of direct and indirect impacts also affect the oceans.

FIGURE 3.9 Bycatch on the deck of a shrimp trawler, South Carolina, USA. (Photo by C. Safina)

This is underscored by the fact that over the next few decades the human population is expected to grow by more than 3,000,000,000 people (~50 percent increase; United Nations Educational, Scientific, and Educational Organization [UNESCO] 2001). By the year 2025, UNESCO (2001) forecasts that population growth and migration will result in a situation in which 75 percent of the world human population will live within 60 km of the sea. Such a migration undoubtedly will change coastal landscapes and nearshore waters that, in many areas, are already suffering from human impacts. The problems associated with development in these zones will progressively become a greater challenge for conservation efforts, particularly in the developing world, where wildlife conservation is often secondary to other national needs. They underscore the need to develop and implement management strategies that balance human population growth, development, and economic activities with the needs of ocean ecosystems.

Structural impacts to coastal habitats include the construction of buildings and pilings, beach armoring and renourishment, and sand extraction (Bouchard et al. 1998). In addition, coastal development is usually accompanied with artificial lighting, which is detrimental to sea turtle hatchlings as they emerge from their nests.

One of the most widespread indirect habitat modifications within coastal foraging areas has occurred due to the vast depletion of green turtles. The associated loss of ecological function has negative implications for the maintenance of both marine and terrestrial ecosystems (McClenachan et al. 2006). As large herbivores, green turtles affect sea grass productivity and abundance (Bjorndal 1980; Zieman et al. 1984) and continue to represent an essential trophic pathway over expansive coastal marine habitats (Thayer et al. 1982, 1984; Valentine and Heck 1999). Through egg deposition on beaches, sea turtles act as biological transporters of nutrients and energy from marine to terrestrial ecosystems (Bouchard and Bjorndal 2000). Thus, with most green turtle stocks substantially depleted relative to historic levels, it is likely that today's coastal marine and terrestrial systems are dramatically modified (Jackson 1997, 2001). The fact that the total adult green turtle population for the entire pre-Columbian Caribbean population ranged from somewhere between 16 million and 660 million turtles (combined estimates from Jackson 1997; Bjorndal et al. 2000) and were regulated by the availability of turtle grass (*Thalassia testudinum*) underscores just how much the current green turtle population, and coastal habitat, has changed.

There are several additional factors that are global phenomena, and though their effects may presently be subtle, the long-term implications are devastating. The impacts from global warming, while not necessarily major today, are likely to become more apparent in future years, especially when they coincide with pollution and overfishing (Nordemar 2004). As global temperatures continue to increase, so will sand temperatures, which in turn will alter the thermal regime of incubating sea turtle nests and alter natural sex ratios within hatchling cohorts. The pending sea-level rise from global warming is also a potential problem, as this will inundate coastal sites and decrease available habitat for nesting turtles as well as haul-out pinnipeds such as seals and sea lions (Baker et al. 2006; Daniels et al. 1993; Fish et al. 2005).

Additional factors affecting marine species and their coastal areas, albeit more localized than those mentioned above, include boat traffic and its modification of the behavior of a variety of species such as dolphins, sea turtles, sea birds, and pinnipeds in coastal areas.

To summarize, the cumulative impact of putting too much in, taking too much out, and destroying the edge of the ocean is that we have fundamentally altered the global marine ecosystem (Halpern et al. 2008) and will continue to transform it in ways that negatively effect us economically, socially, and physically, into the foreseeable future (Worm et al. 2006).

3.5. SUSTAINING WHAT REMAINS, RESTORING WHAT'S BEEN LOST

If the transformation of the world's ocean is described as having put too much in, taken too much out, and destroyed the "edge," a general call to action would include initiatives focused on putting less in, taking less out, and instituting measures to protect portions of the "edge," where biodiversity and productivity are high (Gray 1997).

Our success at restoring and sustaining the ocean depends entirely on the ability of scientists, managers, industry, and stakeholders to collaborate and communicate. For researchers, it is increasingly clear that an interdisciplinary approach that takes full advantage of modern sharing and conferencing technologies is emerging. Symposia that engage stakeholders are increasingly common and the products of such collaborations are often rapidly disseminated.

Such efforts are under way in the form of global biodiversity mapping initiatives, Duke University's Project GLOBAL and OBIS-SEAMAP, the Consortium for Ocean Leadership's Census of Marine Life, regional, national, and international accords aimed at reducing marine debris and ocean pollution, and various collaborative networks advancing ocean science and the establishment of marine protected areas.

New technology can help practitioners expand network building and strategic communication as central rather than subsidiary parts of the conservation mosaic (Nichols 2006). Accompanying this is the need for changes in the way agencies conduct themselves, including enhanced negotiation, communication, and greater flexibility (Mahant 2002).

Scientists have described and advocated ecosystem-based management. A politically and administratively feasible method for translating this concept into an operational management practice has been elusive. Place-based management (PBM) of marine ecosystems calls for integrated management of human activities occurring in spatially demarcated areas identified through a procedure that takes into account biophysical, socioeconomic, and jurisdictional considerations (Mace et al. 2006). PBM offers a way to minimize the costs of obtaining the feedback required to manage complex marine systems sustainably and offers a practical way to solve this problem by taking a comprehensive and integrated approach to managing the human activities in a place rather than dividing management according to individual sectoral themes (Young et al. 2007).

The management of ocean ecosystems, marine megavertebrates, and sea turtles particularly is facilitated by cooperation through a number of regulatory instruments at international, regional, national, and local levels (Hykle 2002). As a result of these designations and agreements, many of the intentional impacts directed at these species have been lessened. Similarly, marine mammals are protected by a variety of treaties, and the International Whaling Commission limits the direct harvest of these species (Hamazaki and Tanno 2001). The harvest of sea turtles, for example, has been slowed at several areas through nesting beach conservation efforts, and an increasing number of community-based initiatives are in place to slow the take of turtles in foraging areas (Fleming 2001). Moreover, there is now a more internationally concerted effort and multisector cooperative research to reduce sea turtle interactions and mortality in artisanal and industrial fishing practices by using time-area closures, gear restrictions, technical fixes, refuges, and marine protected areas (Lewison et al. 2004; figure 3.7).

Experience with protected areas on land demonstrates that they are generally too small to curtail the decline of most species they seek to protect. Species decline continues in these areas because reserves are not big enough to encompass ecosystem processes, such as interdecadal variability, dispersal, and succession. Larger protected areas maintain ecosystem level processes better. For example, seabirds in the central Pacific forage in association with tuna schools (Jaquemet et al. 2004). Large, continuous protected areas encompassing foraging areas, breeding grounds, and the routes in between can help safeguard these types of processes.

Despite these advances, human impacts on the environment continue to expand throughout the world. The lack of effective monitoring in pelagic and near-shore fisheries operations still allows substantial direct and indirect mortality, and the uncontrolled development of coastal and marine habitats threatens to destroy the supporting ecosystems of long-lived marine species. Although several international agreements provide legal protection for marine species, additional multilateral efforts are needed to ensure they are sufficiently implemented and/or strengthened, and key nonsignatory parties need to be encouraged to accede. Each has pros and cons, but it is believed that an institutional mosaic, facilitated by advances in information and communication technology, will be the only way to provide broad protection to marine resources.

Building diverse, collaborative networks of managers, academics, producers, and the public will allow for new information to be shared and will permit new "best practices" to be implemented, crucial to restoring and maintaining ocean health. As such, dissemination theory, communication sciences, and information systems design can combine to advance ocean management and to build a stronger constituency. Lessons from the marketing and media sectors can also be applied to more effectively describe the problems and solutions to our ocean crisis to the minds of billions of people.

3.6. THE NEW PARADIGM: ONE OCEAN, INDIVISIBLE, ESSENTIAL TO LIFE

Breathing. Eating. Most people do not think of the ocean when they do these things. From the Iraqi desert to the San Francisco Bay, our air, food, and climate are the products of an oceanic life support system reaching across every manmade political boundary.

A U.S. senator and governor, Gaylord Nelson, once famously noted, "The economy is a wholly owned subsidiary of the environment, not the other way around" (Nelson 2002). Ecological thinkers understand that the engine of this global economy runs on saltwater. Plankton in the Mediterranean may be providing the oxygen in the air that fills our lungs. Ocean currents such as the Gulf Stream may control our weather and dictate our shipping routes and make or break fishing seasons, and the ocean is the ultimate heat sink—a buffer against rapid global warming.

The ocean is home to some 80 percent of the world's creatures, and these animals respect no political boundaries. Consider that a single molecule of seawater can circulate through the great ocean "conveyor belt" in one thousand years (figure 3.10). Unavoidably, how we live in one place matters to people living on another coast half a world away. Sea turtles, whales, tuna, and sharks weave together the ocean world with their thousand-mile migrations. A sea turtle born in Mexico is not a "Mexican turtle" when it grazes on a coral reef in Hawaii or plucks jellyfish from Indonesian seas.

Thanks to the work of many organizations and agencies, a broad movement is under way to secure our coastal waters and safeguard our ocean (Chaloupka et al. 2007). Politicians courageously defend healthy ocean systems in nonpartisan efforts by supporting coastal protection, fisheries management, and scientific research. But a productive and abundant ocean will require more than strong nationalistic protections. Our efforts must be broad and deep—oceanic in nature.

We need multiple, independent, overlapping sets of observations of ocean processes from space, the ocean surface, and its depths so that we can create long-term records and have confidence that they are accurate. We need integrated theories about how the parts of the ocean system are related to each other so that we can make sense of our observations. We need robust, adaptive models to help us see into the future.

Most urgently, we need immediate and revolutionary changes in our fisheries, agricultural practices, and emissions of greenhouse gases on a global scale, and we must exemplify the changes we hope for (Bearzi 2009; Jackson 2008).

Echoing Aldo Leopold, thanks to exploration and technology, we are now able to "see and feel" much more of the ocean than we were even a few

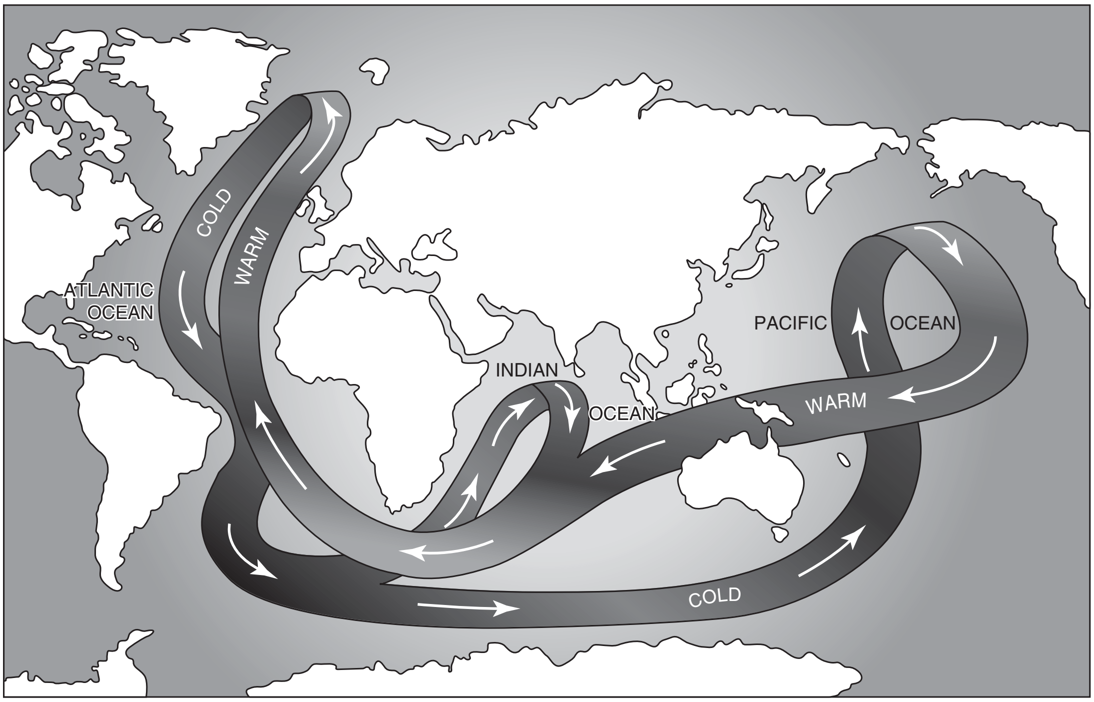

FIGURE 3.10 This conceptual illustration of the ocean conveyor belt circulation illustrates the 1,000-year-long cycle. Warm, shallow water is chilled in the far North Atlantic, grows saltier, and sinks. The cold, salty current flows south near the bottom, creating a northward surface layer flow of the warm, less salty water. (Courtesy of Argonne National Laboratory)

decades ago. The question remains, will we "understand, love or otherwise have faith in" the ocean's central role in our lives, change our destructive behaviors, and learn to sustain the abundance and evolving diversity of the seas?

To take on the pressing issues facing our ocean planet, we need creativity, innovation, and resolute people who understand that it is one ocean, indivisible and essential, after all.

As Aldo Leopold observed in *A Sand County Almanac* (1948/1987), "A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it tends otherwise."

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