MARINE CONSERVATION

Science, Policy, and Management

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CHAPTER 2

MARINE CONSERVATION ISSUES

> . . . man has greatly reduced the numbers of all larger marine animals, and consequently indirectly favored the multiplication of the smaller aquatic organisms which entered into their nutriment. This change in the relations of the organic and inorganic matter of the sea must have exercised an influence on the latter. What that influence has been, we cannot say, still less can we predict what it will be hereafter; but its action is not for that reason the less certain.
>
> George Perkins Marsh (1864) *Man and Nature: Or Physical Geography as Modified by Human Action*.

2.1 IGNITING MARINE CONSERVATION CONCERN

Issues attract conservation concern for changes threatening marine biological richness and ecosystem function. Marine ecosystems sustain the largest species on Earth (blue whale), the fastest swimmers (mako shark, marlins), the most bizarre (octopus), most serene (kelp forests, coral reefs), most intriguing (dolphins, orcas, sea horses), most fearsome (great white shark), and most tasty (shellfish, salmon). Depletion of some species, overabundance of others, ill health, and degradation of habitats are *primary* issues for concern, followed by *secondary issues* that illustrate the concentration of human activities impinging on marine ecosystems. *Tertiary issues* focus on fundamental changes in marine ecosystems that are global in scope and propelling marine ecosystems toward unexpected and unintended outcomes. These issues, largely hidden beneath the undulating waves, contrast with a seemingly resilient ocean undergoing change, with major social and economic consequences.

2.2 PRIMARY ISSUES: LOSS OF MARINE BIODIVERSITY

Scientific evidence makes clear that marine ecosystems are losing some of their largest, most charismatic and most productive species. Overabundance of nuisance and toxic species, ill health and pandemics, abnormal behaviors, and deteriorating critical habitats highlight biological changes in the marine environment. This set of issues focuses conservation concern on the ethical and ecological loss of species and marine biological diversity, moving marine environments increasingly toward biological homogenization with consequences for ecosystem integrity and function.

2.2.1 Species extinctions and depletions

Many of the largest and most charismatic marine species, the icons of the oceans, are being depleted worldwide and/or risk extinction. The IUCN 2008 *Red List of Threatened Species* documents about 1500 marine species (Polidoro *et al*., 2008; Fig. 2.1). Documented extinctions of less obvious species are few (e.g., sediment fauna; Snelgrove *et al*., 1997), but ramifications could be significant (Emmerson *et al*., 2001). The ability of scientists to anticipate extinction is elusive, and understanding the causes is a central problem in biology (Ludwig, 1999).

Of the more than 120 species of marine mammals, at least a quarter is presently depleted (Polidoro *et al*., 2008), and a few have gone extinct. The Steller sea cow (*Hydrodamalis gigas*) was wastefully hunted to extinction 27 years after its discovery in 1741 (Stejneger, 1887; Fig. 2.2); its living Sirenian relatives, the dugongs (*Dugong dugon*) and manatees (*Trichechus* spp.), face potential extinction. Whaling drastically reduced the great whales and recovery of some is slow. The North Atlantic gray whale (*Eschrichtius robustus*) population went extinct in the 18th century, but the relatively rare, iconic blue whale (*Balaenoptera musculus*) appears to be recovering. Right whales (*Eubalaena glacialis*) remain at risk in the North Atlantic and North Pacific (the latter was victim of illegal whaling, Box 3.1), but the Southern Hemisphere population is rapidly recovering (FAO, 2011). The sperm whale (*Physeter macrocephalus*) of *Moby Dick* fame has recovered to 32% of pre-whaling levels (Whitehead, 2002). A declining population of the iconic orca or "killer" whale (*Orcinus orca*) in Washington State is in danger of extinction due to reduced prey and toxic pollution (Wiles, 2004). The Gulf of California porpoise (*Phocoena sinus*) and all river dolphins (family Platanistidae) are greatly depleted and near extinction; the Chinese Yangtze River dolphin (*Lipotes vexillifer*) is considered extinct (Turvey *et al*., 2007). The seriously depleted Mediterranean (*Monachus monachus*)

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and Hawaiian monk (*M. schauinslandi*) seals may be following the now extinct Caribbean monk seal (*M. tropicalis*) that was last reliably sighted in the 1950s near Jamaica. International protection of fur seals (*Callorhinus* and *Arctocephalus* spp.) and sea otters (*Enhydra lutris*) prompted their recovery from near-extinction during the 19th century's fur and oil exploitation, although some are currently declining for unknown reasons (Ch. 7). Atlantic walruses (*Odobenus rosmarus rosmarus*) remain depleted to this day, following a centuries-long period of exploitation; the Pacific subspecies (*O.r. divergens*) recovered following the collapse of Bering Sea whaling, but appears now to be declining (Ch. 7).

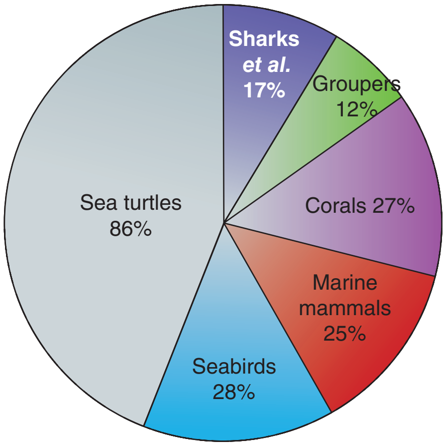

Fig. 2.1 Percent marine species in taxonomic groups are listed in the *Red List of Threatened Species* as Critically Endangered, Endangered, and Vulnerable to extinction (IUCN, 2012). The number of marine species assessed for extinction lags far behind those on land. Percents of Red-Listed species of sharks and rays, groupers, reef-building corals, seabirds, marine mammals, and sea turtles have been calculated from data in Polidoro *et al.* (2008).

Many seabirds are in serious decline. Some 312 species (albatrosses, penguins, puffins, auks, etc.) in 17 families are vulnerable to extinction due to their dual dependence on land and sea, which subjects them to both terrestrial development and marine fishing activities (Ballance, 2007). Of particular concern are petrels and albatrosses that migrate over great ocean distances to feed and return to land to breed. Coastal pollution and climate change increase the threat.

Sea turtles are also threatened with extinction due to dual dependence to breed on sandy beaches and long-life ocean feeding (NRC, 2010a). Their sea migrations cover whole ocean basins (Ch. 8) where fisheries bycatch is an especially serious form of mortality. All seven species of these air-breathing reptiles face direct and indirect human impacts: loggerhead (*Caretta caretta*); green (*Chelonia mydas*); hawksbill (*Eretmochelys imbricata*); Kemp's ridley (*Lepidochelys kempii*); olive ridley (*Lepidochelys olivacea*); leatherback (*Dermochelys coriacea*); and flatback (*Natator depressus*).

Fishes are by far the most diverse and numerous of vertebrates, and the list of threatened and depleted species is long and growing. Many of the largest are targeted by commercial and sports fisheries, and examples are many. The largest and fastest tuna and billfish are depleted as a result of high market

Fig. 2.2 Extinct Steller sea cow (*Hydrodamalis gigas*) as conceived from existing sources. This herbivorous marine mammal, exploited to extinction, was the largest member of the order Sirenia, a group that includes dugongs (*Dugon dugon*) and manatees (*Trichechus* spp.). All four extant species of this group are listed by IUCN as Vulnerable to extinction. Illustration © R. L. Smith, Jr.

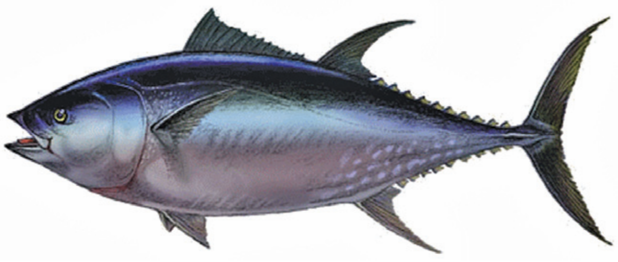

Fig. 2.3 Atlantic bluefin tuna (*Thunnus thynnus*), is the largest of tuna (4 m long and weighing up to nearly 900 kg), a prime target for game and longline fishing, and a favorite for sushi. This highly migratory, top predator has declined more than 80% since the 1970s and is listed by IUCN as "Endangered" (IUCN, 2012). Illustration © R. L. Smith, Jr.

value that encourages overfishing. The largest of them, the Atlantic bluefin tuna (*Thunnus thynnus*; Fig. 2.3), is subject to intense fishing pressure and may be on the path to extinction (IUCN, 2012). The depleted great white shark (*Carcharodon carcharias*) has a low reproductive potential (Smith *et al.*, 1998). Other sharks (e.g., scalloped hammerhead (*Sphyrna lewini*), thresher shark (*Alopias vulpinus*), etc.) have declined more than 75% just in the last 15 years (Baum *et al.*, 2003); coastal sand tiger sharks (*Carcharias taurus*) of the Atlantic, Caribbean, and Gulf of Mexico are threatened by poor water quality, fishing, and fisheries bycatch (Meadows, 2009). Sawfishes (*Pristis* spp.) and some species of skates and rays (order Rajiformes) are threatened worldwide due to fisheries bycatch and gill-net fishing. The 5.5 m shallow-water smalltooth sawfish (*P. pectinata*) is in a critical state. Estuarine fishes that travel between land and sea to breed and feed (salmons, sturgeons, anguillid eels) are particularly vulnerable; natural populations of Atlantic salmon (*Salmo salar*) are seriously depleted, as are southerly northwest Pacific populations of five species of salmon (*Oncorhynchus* spp.). Groupers as a whole, especially the tropical West Atlantic Nassau grouper (*Epinephelus striatus*), are much depleted (Ch. 8). Deep-living ocean fish are also especially vulnerable; the slow-growing, late-to-mature orange roughy (*Hoplostethus atlanticus*), which lives below 200 m in the deep sea, is especially vulnerable to fishing, due to a low reproductive rate, and is greatly depleted.

Invertebrates are particularly difficult to assess due to their overwhelming numbers, variety, and lack of high conservation priority. Iconic corals and some shellfish are approaching extinction from a variety of causes. Tropical corals, especially the historically abundant Caribbean reef-building elkhorn (*Acropora palmata*) and staghorn (*A. cervicornis*) corals are now much reduced (Ch. 8). Two rare endemic coral species of the Galápagos Archipelago (*Tubastraea floreana* and *Rhizopsammia wellingtoni*) are declining, presumably due to climate change. Abalone, in particular white (*Haliotis sorenseni*) and black (*Haliotis cracherodii*) abalones of the Northwest Pacific, as well as the perlemoen (*Haliotis midae*) of South Africa (Ch. 11), are prized food items and key members of coastal ecosystems, and face high risk of extinction.

2.2.2 Overabundant species

Conversely to depletion, some species are flourishing beyond expected levels. Overabundance reflects a species' ability to dominate a natural community and become a nuisance or harmful. This situation is often the result of an unnatural (deliberate or accidental) transfer of a species (termed alien, exotic, invasive) into a new location, where it can thrive with few natural controls, and outcompete native species. Even relatively uncommon species in their native environments can prove successful in changed environments or when their predators are absent, reproducing in such massive numbers that they can deplete their own food resources (e.g., sea urchin "barrens"; VanBlaricom and Estes, 1988). And some native species may thrive, for example, the common reed (*Phragmites*) in North American wetlands (Box 2.1). Others may transform ecosystems into monocultures, later to crash and leave barren seascapes.

Increasingly, exotic species introduced by human activities into new locations are transforming environments; coastal waters appear to be particularly vulnerable (Preisler *et al.*, 2009). About 329 marine invasive species are documented for 84% of the world's 232 marine ecoregions (Molnar *et al.*, 2008). Most are benign, but some can transform marine habitats, displace native species, alter community and ecosystem structure through nutrient cycling and sedimentation patterns, damage fisheries, and clog ship hulls and power plants. A particularly severe invasion is that of the lionfish (*Pterois volitans*) in The Bahamas (Ch. 8). The social and economic consequences are major national and global concerns (Vitousek *et al.*, 1996).

Sea plants globally have invaded new environments in unprecedented numbers. A fast-growing exotic alga (*Caulerpa* sp.) is transforming parts of the Mediterranean Sea's benthos into dense, single-species cover; *Caulerpa* has also invaded southern California and Australia. Sea lettuce (*Ulva prolifera*) formed a massive green tide on the popular tourist beaches of Brittany, France (June 2008), that killed dogs, a horse, and a clean-up worker. This alga reappeared in 2011 to rot en masse, releasing massive amounts of hydrogen sulfide gas (H_2S) that killed 36 wild boars (Hu *et al.*, 2010). Sea lettuce also blooms massively in the East China and Yellow seas; another green alga (*Enteromorpha prolifera*) covered 13,000–30,000 km^2 in the Yellow Sea (Sun *et al.*, 2008).

Exotic species can disrupt flows of energy and materials and biogeochemical pathways important to nutrient recycling, thus altering whole ecosystems. Such species may also alter evolutionary routes important to biodiversity, habitat stability, and ecological biomass (Crooks, 2009). For example, the European intertidal common periwinkle (*Littorina littorea*) that invaded New England shores changed mud flats and salt marshes into rocky shores by grazing on stabilizing algae and marsh grass (Williamson, 1996).

Natural phytoplankton blooms described as "red tides" (dinoflagellates; Fig. 2.4), "green films" (cyanobacteria), "brown tides" (chrysophytes), and micro-planktonic algae (dinoflagellates, blue-green algae, diatoms) are increasingly discoloring coastal waters and some are toxic, e.g., harmful algal blooms (HABs; Anderson, 2004). Blooms may remain localized or

Box 2.1 Invasion of common reed (*Phragmites*) in North American wetlands

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Wetlands are often sites of invasion by non-native species of plants (Zedler and Kercher, 2004). In the U.S., one of the most abundant, conspicuous, and notorious invaders is common reed, *Phragmites australis*, a grass that grows in dense stands up to 3–4 m tall, effectively blocking the growth of other potential plant competitors (Meyerson *et al*., 2009). *Phragmites* is considered a “cryptic invader” (Saltonstall, 2002) because an invasive genotype, introduced from Europe around the advent of the Industrial Revolution (Saltonstall *et al*., 2004), can displace the native subspecies. The native typically is a minor component of wetland communities, so the expansive growth of exotic *Phragmites* monocultures eliminates many other species as well.

The negative consequences of invasion and subsequent expansion of *Phragmites* into both tidal and non-tidal wetland environments include loss of wetland biodiversity and shifts in ecosystem structure and function (Chambers *et al*., 1999). With significant assimilation and storage of water and nutrients (Mozdzer and Zieman, 2010), a *Phragmites*-dominated wetland exhibits patterns of energy flow through food webs and nutrient cycling different from that of the native plant community. *Phragmites*-dominated wetlands tend to be drier than those they displace, with consequences for fish use of these habitats (Osgood *et al*., 2006). Further, bird use of *Phragmites* wetlands tends to include more generalist species than wetland specialists.

Exotic *Phragmites* invades open space in wetlands via both seed and rhizome dispersal (McCormick *et al*., 2010). During the 20th century, U.S. *Phragmites* invasion was tied to human activities in wetlands (Bart *et al*., 2006). Shoreline development that extended from uplands to wetland borders created nitrogen-enriched habitat into which *Phragmites* could establish (Silliman and Bertness, 2004). Some researchers suspect that eutrophication of waterways in North America creates conditions that encourage the introduction and spread of *Phragmites*. Interestingly, however, those same nutrient-rich conditions have been cited as a possible cause of *Phragmites* die-back in some parts of Europe.

Owing in part to the “no net loss” policy of wetland mitigation in the U.S., created wetlands provide additional open space for invasion and expansion of *Phragmites*, as *Phragmites* is one of the first species to arrive and thrive in these sites (Havens *et al*., 2003). At present, even undisturbed, pristine wetlands are susceptible to invasion, perhaps due to nitrogen enrichment via atmospheric deposition. *Phragmites* now occurs in wetlands from all 48 of the conterminous United States. Along the middle Atlantic seaboard, a broad invasion “front” appears to be working south through Virginia and the Carolinas. Some wetlands are taken over by *Phragmites* quickly, whereas others seem more resistant to invasion. *Phragmites* has also spread northward into eastern Canada, where yet another invasive species (purple loosestrife, *Lythrum salicaria*) is considered a bigger threat to native biodiversity.

Efforts to stop *Phragmites* expansion using controlled burning, chemical spraying, and physical removal have been largely unsuccessful. Without chronic application of these methods every growing season, *Phragmites* stands tend to recover more quickly than other species. Bio-control methods are under development but run the risk of non-specific actions by the control agents; a number of rhizome-boring insects have been introduced accidentally from Europe, but their North American impacts on *Phragmites* and potentially on other species have not been assessed (Tewksbury *et al*., 2002). From a management perspective, most invaded wetlands cannot be restored to a pre-*Phragmites* condition. Many coastal wetlands that once were restricted to tidal flows have been re-opened, allowing extended flooding by anoxic saltwater sufficient to kill *Phragmites* and encourage re-establishment of natives. However, managers often cannot exercise this option and must accept ecological changes brought on by a new wetland dominant.

Managing non-native *Phragmites* invasion is also complicated by the presence of the native, less aggressive genotype of *Phragmites* that is losing ground. How can *Phragmites* be managed to maintain the native and kill the exotic? Recent research has demonstrated that hybridization between native and non-native genotypes is possible (Meyerson *et al*., 2009), further limiting the available options for control of the abundant invader. Despite the negative impacts of having such an aggressive species in wetlands of North America, non-native stands are significant sinks for nutrients and may be important in mitigation of polluted, non-point source runoff to waterways. Because of rapid, extensive root and rhizome growth, *Phragmites* may also serve to stabilize shorelines in the face of coastal erosion and rising sea level. Additionally, in European and Asian wetlands where it has grown for centuries, *Phragmites* is used for thatching roofs and for paper production; this practice also occurs in portions of the U.S. by immigrants. Because of these positive qualities valued by humans, the new invasion and overabundance of exotic *Phragmites* cannot be easily categorized as either a bane or a blessing. Appropriate policy and management decisions regarding the invasion and spread of *Phragmites* must be considered within site-specific social and ecological contexts.

Fig. 2.4 Algae bloom, popularly known as "red tide." Small inserted picture illustrates two microscopic toxic dinoflagellates that cause red tide blooms. Photograph © Ray & McCormick-Ray. Dinoflagellates from U.S. Public Health Service online.

cover thousands of square kilometers for weeks; some occur at the same time and place each year and others are unpredictable, as for example: *Alexandrium fundyense* in the Gulf of Maine (Anderson *et al.*, 2005); *Karenia brevis* in the Gulf of Mexico (Steidinger *et al.*, 1998; Vargo, 2009); cyanobacteria in the Baltic Sea (Kononen, 1992; Bianchi *et al.*, 2000); and others (Pitcher and Pillar, 2010). HABs produce toxins, noxious gases, or anoxic water that kill marine life, and are becoming more frequent. Some produce a neurological biotoxin (domoic acid) that causes amnesic shellfish poisoning that affects people and a variety of sea life from fish to blue whales (Grant *et al.*, 2010). Some dinoflagellate HABs (e.g., *Alexandrium* sp., *Gymnodinium* sp., *Pyrodinium* spp., etc.) produce saxitoxin, also a neurotoxin that caused massive humpback whale mortality in 1987 (Geraci *et al.*, 1989). A toxic dinoflagellate (*Noctiluca scintillans*) bloom stretched more than 20 miles along the California coast in 1995 (Anderson, 2004); another killed more than 1600 New Zealand sea lion pups (*Phocarctos hookeri*) at Auckland Island in 1998. And the first known toxic dinoflagellate bloom (*Gymnodinium* sp.) in the Arabian Sea in 1999 killed fish, closed aquaculture facilities, and caused significant economic impact (Heil *et al.*, 2001). Toxic algae not only affect sea life, but also alter marine food-chain structure and habitats, and are linked to public health, seafood safety, and aquaculture, causing human deaths and illnesses and threatening coastal areas (Stommel and Watters, 2004).

Dense aggregations of jellies ("jellyfish") are increasing in severity and frequency worldwide (Parsons and Lalli, 2002; Graham and Bayha, 2007; Richardson *et al.*, 2009). Overabundant jelly animals (pelagic cnidarians, ctenophores) may cause severe threats to ecosystem function on massive scales (Graham *et al.*, 2003), with most notable blooms occurring in the Far East and East Asian marginal seas (Uye, 2008; Dong *et al.*, 2010). Jellies are a natural feature of healthy pelagic ecosystems; in the Far East three species (*Aurelia aurita, Cyanea nozakii, Nemopilema nomurai*) naturally form large blooms. However, the population of the giant jellyfish *N. nomurai* (2 m maximum bell diameter, 200 kg wet weight) in Southeast Asia increased 250% between 2000 and 2003 with 300–500 million medusae being observed in 2005 (Uye, 2008). In Japan, moon jellyfish (*Aurelia* sp.) clog power plant intake lines (Purcell, 2005). The American comb jelly (*Mnemiopsis leidyi*) that invaded the Black Sea bloomed in the late 1980s to reach concentrations of 300–500 animals per m^3, with a biomass in some regions of over a billion tons (Mills, 2001); it also spread into other European seas, including the central Baltic, causing concern for fisheries. Overfishing, eutrophication, climate change, translocation, and habitat modification may contribute to blooms of jellies. Such abundance reduces food for fishes, alters food webs, and collapses fisheries to impact fishermen and national economies.

2.2.3 Ill health

Diseases of sea life, expressed as lesions, deformities, and infections, are collectively referred to as "ill health." Region-wide epidemic diseases of a wide variety of taxa have caused massive die-offs. Such phenomena appear to be increasingly frequent globally (Harvell *et al.*, 1999). Examples are numerous. Corals worldwide exhibit "bleaching" due to loss of zooxanthellae (Fig. 2.5a). Caribbean corals exhibit microbial infections in epidemic proportions described as "white pox," "black line," and fungal diseases (Goreau *et al.*, 1998; Fig. 2.5b). Reef-building Caribbean corals are also infected by the bacterium *Vibrio* sp. (Cervino *et al.*, 2004). High mortalities of Caribbean sea fans (*Gorgonia ventalina*) caused by a worldwide terrestrial fungus (*Aspergillus sydowii*) carried on airborne dust from Africa (Weir-Brush *et al.*, 2004) were related to ocean warming and nutrient enrichment (Ellner *et al.*, 2007). Sponges worldwide are exhibiting significantly more diseases, with decimated populations throughout the Mediterranean and Caribbean seas (Webster, 2007). A "wasting disease" caused by a slime mold (*Labyrinthula macrocystis*) extirpated North Atlantic eelgrass (*Zostera marina*) in 1931–2, and 10 other species are

Fig. 2.5 Examples of diseased marine species. (a) Bleached fire coral (*Millepora* sp.). Photograph © Ray & McCormick-Ray. (b) Blackline coral disease (*Montastrea* sp.). Photograph © Ray & McCormick-Ray. (c) Green sea turtle with viral tumors, fibropapillomatosis, Andros Island, Bahamas. Photograph © Karen Bjorndal. (d) California sea lion (*Zalophus californianus*) with poxvirus (parapox). Reproduced with permission of The Marine Mammal Center, Sausalito, California. Disease patterns in the ocean are diverse, making it difficult to discern a clear increasing trend (Lafferty *et al.*, 2004).

at elevated risk of extinction with three more qualifying as endangered (Short *et al.*, 2011). Only recently have some species shown signs of slow recovery (Godet *et al.*, 2008).

Vertebrates are also affected. Fishes exhibit a wide variety of well-studied diseases, some caused by humans (Noga, 2000). Sea turtles are infected by a herpes virus that causes multiple cutaneous masses called fibropapillomatosis, associated with heavily polluted coastal areas, areas of high human density, or where agricultural runoff and/or biotoxin-producing algae occur (Fig. 2.5c; Aguirre and Lutz, 2004). Marine mammals, e.g., seals and polar bears, also exhibit epidemic diseases, including a highly contagious, incurable, and often deadly disease called canine distemper virus (CDV) caused by a morbillivirus (de Swart *et al.*, 1995), which is a leading cause of death in unvaccinated dogs. In 1987, many freshwater Baikal seals (*Phoca sibirica*) died from CDV. Other significant morbillivirus species include dolphin morbillivirus (DMV), porpoise morbillivirus (PMV; Saliki *et al.*, 2002), and in pinnipeds, phocine distemper virus (PDV). PDV killed more than 23,000 harbor seals (*Phoca vitulina*) in Europe in 1988 and 30,000 in 2002 (Härkönen *et al.*, 2006) and has been reported for sea otters (*Enhydra lutris*) in the North Pacific Ocean (Goldstein *et al.*, 2009). DMV and PMV are now considered the same species, renamed cetacean morbillivirus (CMV). Viruses have also caused mortalities among striped dolphins (*Stenella coeruleoalba*), endangered Mediterranean monk seals (*Monachus monachus*), and fin whales (*Balaenoptera physalus*). Viral infections and pollutants were implicated in the deaths off U.S. mid-Atlantic shores of more than 700 bottlenose dolphins (*Tursiops truncatus*) in 1987–8, and in excess of 500 harbor seals in New England waters in 1979–80. This massive mortality caused by an influenza virus carried by birds killed 3 to 5% of the 10,000 to 14,000 seals along the New England coast (Geraci *et al.*, 1982). Viruses also infect California sea lions (Fig. 2.5d).

Ill health brings into question: what is normalcy? Are diseases in the ocean increasing (Lafferty *et al.*, 2004), are they new, or are they re-emergent (Harvell *et al.*, 1999)? Much remains to be known about the “normal state” of health for most marine species. Nevertheless, the magnitude of such phenomena and extent are difficult to ignore.

2.2.4 Abnormal behaviors

Although normal behaviors of most marine species are poorly known, changes in species distributions and behavior such as altered breeding times and places are being increasingly reported. For example, some migratory waterfowl that normally feed on shallow-water vegetation consume farm crop residues and no longer migrate. Expanding numbers of gulls opportunistically feed in garbage dumps and around fishing boats. California sea lions are choosing docks and piers rather than natural shores to rest, and Florida manatees seek the warm-water effluents of power plants during cold winters. Some cetaceans are hybridizing with other species (Zornetzer and Duffield, 2003), a phenomenon apparently unique among mammals (Willis *et al.*, 2004), but that may be normal for Cetacea.

Increasing interactions with humans are proving to be aggressive, mutualistic, positive, or learned. Shark attacks on humans are not common, but raise much public concern and speculation. Sharks' decreasing numbers do not translate into reduced attacks on humans, possibly because of increased numbers of swimmers and divers in nearshore waters (West, 2011). Sharks are not alone; dolphin (*Tursiops* sp.) interactions with humans in Monkey Mia in western Australia have turned aggressive (Orams *et al.*, 1996; Orams, 1997), betraying the illusion of their friendly behavior toward humans.

2.2.5 Critical habitat degradation

Marine life depends on habitats, which are increasingly being modified, fragmented, and lost. Such changes worldwide are seriously threatening many species (Sih *et al.*, 2000). At the interface of land and sea, coastal habitats include salt marshes (Box 2.2), estuaries (Ch. 6), mangroves, reefs, and seagrasses (Ch. 7) that are particularly under severe threat worldwide, being increasingly exposed to poor water quality and erosion. Islands and sandy beaches are disappearing, exacerbated by interactions between human activities, tsunamis, hurricanes, and global warming. Most notably in the Indian Ocean, the 1200 islands and atolls composing the island nation of the Maldives are threatened by inundation due to sea-level rise. Loss of coastal habitats and islands is reducing critical ecosystem services that provide social benefits (Barbier *et al.*, 2011).

Estuaries are among the most productive of all ecosystems and vital to fisheries yet face worldwide decline (Lotze *et al.*, 2006). Deteriorating estuarine health is commonly due to poor water quality, depletion of native species (e.g., shellfish, estuarine fishes), and monocultures of invasive species. In the U.S., estuaries are typically over-enriched with nutrients (Bricker *et al.*, 2008). Once diverse and productive, estuaries and coastal seas have lost more than 90% of their formerly important species' populations and more than 65% of their associated seagrass and wetland habitats.

Seagrasses that provide key ecological services are in a global crisis (Orth *et al.*, 2006; Fourqurean *et al.*, 2012). An estimated 29% of their known global areal extent has disappeared since being first recorded in 1879, and losses have accelerated worldwide since 1980 at an annual rate of 110 km^2 (Waycott *et al.*, 2009). Fourteen percent of all seagrass species are at risk of extinction, with nearly one-quarter (15 species) in serious trouble (Short and Wyllie-Echeverria, 1996; Short *et al.*, 2011). Loss of seagrass habitat is attributable to a broad spectrum of anthropogenic and natural interactions—disease, destructive fishing practices such as dredging, nutrient pollution, natural dieback, etc.—affecting dependent fishes, invertebrates, waterfowl, dugongs, manatees, green turtles, and others.

Hard-bottom reefs (oyster, coral) are globally threatened. Temperate oyster reefs have been intensively depleted over a long period, those remaining being only vestiges of their former extents (Ch. 6; Beck *et al.*, 2009). Tropical coral reefs are threatened worldwide (Ch. 8; Box 2.3).

2.3 SECONDARY ISSUES: HUMAN ACTIVITIES

Secondary issues focus on human activities as agents of coastal change. Thirty-eight percent of the world's 6.5 billion people occupy only 7.6% of Earth's total land area—the narrow coastal fringe (UNEP/GPA, 2006). Fishing is the major agent of change, followed by chemical pollution, eutrophication, and invasive species (NRC, 1995). Such resource extraction, additions of novel substances, and physical alterations have historical roots imbedded in the social fabric of the global society. Expanding this level of coastal impact is the physical alteration of watersheds, new dam construction, wetland filling and/or drainage, and coastal armoring. These human activities act cumulatively over time to physically and functionally alter the coastal system on which so many species and a large portion of the global economy depend.

2.3.1 Extractions: over-harvesting natural coastal resources

Human civilizations extract many benefits from the oceans. With increasing technological advances driven by expanding human needs with increasing intensity, activities and impacts are moving ever deeper into the unknown realm of deep-ocean basins.

2.3.1.1 Overfishing

The limits of ocean bounty have been reached, and in some cases exceeded. Whaling drastically reduced the great whales when the International Whaling Commission stopped it in 1982 (Fig. 2.6; Ch. 3). But the seas continued to bring hope of meeting global food shortages (Idyll, 1978), and global fisheries in the 1950s extracted <20 million metric tons (mt) annually. By the late 1980s, expanding fisheries reached maximum global capacity (Pauly, 2008) and have since been declining (Fig. 2.7a); by 2004, 366 fisheries had collapsed, nearly one of four (Mullon

Box 2.2 Salt marshes under global siege

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Salt marshes are hugely productive intertidal grasslands that form in low-energy, wave-protected shorelines along continental margins. For over 8000 years, humans have benefited greatly from salt marshes and relied on them for direct provisioning of materials (Davy *et al*., 2009). For example, starting roughly 2000 years ago and to this day, marsh grasses are still purposely planted and protected by the Dutch so as to act as buffers against storm surges and as natural-engineering tools to reclaim shallow seas and build up sea barriers to facilitate greater human reclamation and development (Davy *et al*., 2009). Indeed, over 40% of the land in present-day Netherlands was once estuarine intertidal mud habitat and was reclaimed with the help of the engineering services of salt marsh plants (Davy *et al*., 2009). Besides this poignant service, salt marshes provide many other valuable benefits to humans, including water filtration, buffering of storm waves and surges, carbon sequestration and burial, critical habitat for both adult and juvenile fishes and birds, grasses for building houses and baskets, land for grazing ungulates and development, and for scientific and educational opportunities.

Despite this list of abundant and valuable critical services, salt marshes are under global siege from an impressive portfolio of human-generated threats (Gedan *et al*., 2009). Salt marsh coverage, as well as the structure of these ecosystems, continues to deteriorate drastically due to human-induced changes. The critical ecosystem services these systems support are likewise endangered. No longer can marshes be viewed in scientific, conservation, social, and political circles as one of the most resilient and resistant ecological communities. And no longer can they be championed as systems that can and should be used to buffer human impacts (e.g., absorption of nutrients in wastewater and terrestrial runoff). These systems are in desperate need of protection from human influence. Most of these threats are currently underestimated or even overlooked by coastal conservation managers because marsh preservation practitioners have historically worried most about stopping reclamation efforts (Silliman *et al*., 2009a). Current threats to salt marshes include human-precipitated species invasions, small- and large-scale eutrophication and accompanying plant species declines, runaway grazing by snails, geese, crabs, and nutria that denude vegetated marsh substrate over vast extents, climate-change induced effects including sea-level rise, increasing air and sea surface temperatures, increasing CO_2 concentrations, altered hydrologic regimes, and a wide range of pollutants, including nutrients, synthetic hormones, metals, organics, and pesticides (Silliman *et al*., 2009a).

Already about 50% of the value of services marshes provide have been lost as salt marsh ecosystems have been degraded or lost (Gedan *et al*., 2009). On some coasts, such as the West Coast of the U.S., this number rises above 90%, for both marsh area and their services (Bromberg and Silliman, 2009). Without proper conservation action, it is now predicted that this key coastal community will become a non-significant, ecosystem-service-generating habitat in <100 years (Silliman *et al*., 2009a). Key to saving salt marsh ecosystems and their services is recognizing a wide variety of threats and abating them through up-to-date conservation strategies (Silliman *et al*., 2009b) and providing justification of these conservation measures by both describing and valuing all of the critical services marshes provide.

One of the most important and effective acts that conservation practitioners can begin to do to ensure the long-term protection and persistence of salt marsh habitats is to champion the use of Marine Protected Areas in marsh management. This has been done widely for reefs, kelps, mangroves, and seagrasses, but not marshes and their surrounding waters. These protected areas must: (i) include associated marine habitats, such as seagrass beds and oyster reefs; (ii) incorporate extensive areas of undisturbed terrestrial border to buffer marshes from excessive eutrophication via runoff and allow for their landward migration as sea-level rises; (iii) account for the inclusion of positive interactions (Halpern *et al*., 2007) at all levels of biological association (e.g., between species—trophic cascades; and across ecosystems—nursery benefits); and (iv) be large, numerous, and appropriately spaced (See Halpern *et al*., 2007 for discussion). Around the world, coral and rocky reef conservation practitioners and scientists lead the field of marine conservation in this effort. Salt marsh conservationists and ecologists are far behind this work and, thus, should look to these fields for lessons-learned and guidance when establishing Marine Protected Areas for temperate coastal areas whose intertidal zone is dominated by salt marshes. Because of the conservation prestige associated with the designation of a site as a Marine Protected Area, using this method as a means to preserve marshes will also raise public awareness as to the critical role marshes play in the ecology and economy of local human communities.

Box 2.3 People and coral reefs

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The complex and diverse assemblages of organisms that compose shallow coral reef ecosystems (<30 m deep) cover a total area of the global tropical ocean approximately the size of the state of Nevada. Coral reefs are ecologically linked to other coastal ecosystems, notably seagrasses, mangroves, and the open ocean, considerably extending their total area and influence. About 90% of shallow coral reefs occur in the Indo-Pacific and most of the remainder is in the Wider Caribbean, including Florida, Bermuda, and the Gulf of Mexico. Corals also form diverse assemblages in deep, cold waters at all latitudes, generally encrusting on the rocky surfaces of deep-sea mounts, but they do not form reefs there. Advances in fishing technology have opened seamounts to trawling and there is increasing international political action to protect deep-water corals.

As the marine ecosystem with the most species, shallow coral reefs are often compared to tropical rain forests. Reefs contain far fewer described plant and animal species than tropical forests, but support almost twice as many phyla (the basic forms of life) as all terrestrial ecosystems combined. This rich biodiversity and the brilliant display of form and color make coral reefs attractive to scientists who explore the origin, maintenance, and functioning of biological diversity. These same characteristics are also attractive to people who draw joy, fascination, and inspiration from the myriad life forms arrayed in intricate patterns in warm, transparent waters.

Coral reefs provide significant and economically important ecosystem services to human societies and are critical to future economic development of ecotourism in many developing countries. Fishing on coral reefs contributes approximately 10% of the world's estimated annual fishery production of more than 80 million metric tons and this protein is mostly locally consumed by coastal communities. As governments look for economic development opportunities, tourism is potentially more economically important than fishing in most places, but fishing will remain an important cultural activity. In an era of projected climate warming, a healthy, robust reef, with growth pacing sea-level rise, protects shorelines and productive coastal lagoons from the erosion of open-ocean waves, storms, and occasional tsunamis. Finally, a significant scientific effort is devoted to prospecting for new drugs and chemical compounds, active, for example, in cancer and AIDS therapies.

Modern coral reefs are the largest biogenic structures in nature. They originated millions of years ago, but reefs of today represent only approximately 6000–10,000 years of post-Pleistocene growth, during the most recent period of sea-level rise. Reefs are essentially cemented piles of coral rock, formed by the limestone skeletons of stony corals and other carbonate-producing organisms (notably calcareous algae), and sand. The living part of the reef is a thin veneer over the reef surface. Corals live in all seas, but the hermatypic, or reef-building, corals are restricted to shallow (<100 m) waters >20°C. Water temperatures much higher than 30°C can be lethal. Hermatypic corals are distinguished by a symbiotic relationship with single-celled, photosynthetic algae called zooxanthellae, which live within the cells of the individual polyps that make up the coral colony and give corals their muted colors of green, red, brown, and yellow. Most corals actively feed by capturing zooplankton with specialized stinging cells on their tentacles, which provides their zooxanthellae with essential nutrients. In return, the coral receives oxygen and photosynthetic products from the algal cells. Healthy, growing coral reefs require high light, wave action, low nutrient levels, and a narrow range of temperature and salinity in order to survive.

Coral reefs have evolved in association with episodic natural disturbances such as tropical storms, sedimentation from terrestrial runoff, and occasional harmful variations in seawater temperature and salinity. However, with over one-half of the world's population now living in the world's coastal zones, coral reefs are increasingly being destroyed by chronic human disturbances such as poor land-use practices, including coastal deforestation; sediment runoff; pollution; diseases; the direct and indirect effects of fishing and aquaculture; destruction of habitat by mining, dredging, and coral collecting; and global climate change.

Coral diseases have been particularly damaging. For example, the abundant and ubiquitous elkhorn coral (*Acropora palmata*), a major Caribbean reef builder, was so dramatically reduced by white band disease over the past five decades that it was listed as threatened under the U.S. *Endangered Species Act*. The impact of this and other diseases has stimulated a major research effort to understand the role of the many bacteria associated with coral mucus. Some coral diseases have been linked to human enteric bacteria from sewage, but these bacteria are ubiquitous in tropical seas, and the conditions that cause some species of bacteria to become pathogenic are not yet fully understood.

Coral bleaching is a special case of disturbance. When corals are subjected to unusually elevated or prolonged periods of seasonal high water temperatures (>30°C), often in concert with other stresses such as sedimentation, they expel their symbiotic algae and bleach, turning pale or white. Bleaching is not necessarily fatal, but can kill corals if it persists. While coral bleaching has been known for a long time, since 1990 bouts of bleaching have

(*Continued*)

increased in severity and global extent, notably in 1998, 2005, and 2010, reducing many formerly vibrant coral reefs to algae-covered rubble piles. These massive and globally coherent temperature events coincide with increasing scientific certainty that the atmosphere and the oceans are warming and that the cause is the well-documented increase in atmospheric carbon dioxide (CO_2), a key greenhouse gas, originating in the steadily increasing combustion of fossil fuels since the start of the mid-19th century Industrial Revolution.

Increased atmospheric CO_2 has another insidious impact on the global oceans. The rising level of CO_2 in the atmosphere has caused increased absorption of CO_2 in the oceans, where it has already reduced the pH by about 0.1 units (i.e., increased ocean acidity by about 30%). This, in turn, reduces the available level of carbonate ion required by the myriad organisms which build skeletal structures from calcium carbonate. Based on models and archaeological records, by the end of this century the amount of CO_2 in the oceans will exceed that of any time in the last 300 million years. Ocean chemistry is complex and we cannot predict at this point what will happen, but what we know so far makes changes in global energy policy ever more urgent.

Taken in sum, human disturbances have already extracted a heavy toll from global coral reefs. Recent estimates of the status of reefs suggest that by 1992, about 10% of the world's coral reefs had been severely damaged; by 2000 this increased to about 25%; and, by 2050, it has been projected that three-quarters of the world's coral reefs may be damaged or destroyed. If reefs are to be saved, an international effort must begin the difficult task of defining a global energy policy, reducing greenhouse gas emissions by phasing out fossil fuels, and implementing alternative energy sources. In addition, within the defined large marine ecosystems of the world it will be critical to implement international management and governance of coral reefs at the geographic scale of the ecosystem processes that sustain them.

Regionally and locally, disturbances to reefs may be identified, and reasonable, almost common-sense, actions for controlling such disturbances as pollution and land runoff may be implemented. Active reef restoration by transplanting corals from coral nurseries is being explored and may prove to be useful in some cases. An ecosystem-based management (EBM) approach combined with modern geographic information systems and modeling holds great promise. Finally, large geographic-scale ocean-use planning incorporating large management and conservation areas, far larger than the relatively small Marine Protected Areas already in place, are required for integrated protection and sustainable human use of these remarkable structures.

In this first century of what some are calling the Anthropocene, the human footprint has extended to almost all parts of the global ocean. Similar to the canary in the mine that warned early Welsh coal miners of the presence of poisonous gases, the sharp decline of coral reefs may be our warning that "business as usual" must, through policy and human behavior, be changed to new models that stress living sustainably with our environment, whose services sustain the biodiversity upon which our future lives will depend.

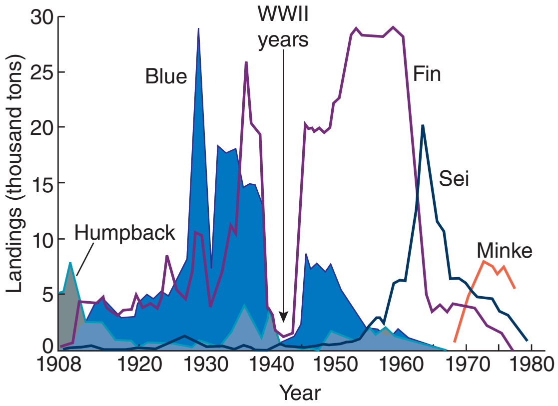

Fig. 2.6 Landings of Southern Ocean baleen whales by commercial whaling, 1908–82. The two largest whales (humpback, *Megaptera novaeangliae*, 11.5–15.0 m; blue, *Balaenoptera musculus*, 24–27 m) were depleted first, then smaller whales (fin, *B. physalus*, 18–22 m; sei, *B. borealis*, 12–16 m; minke, *B. acutorostrata*, 7–10 m). World War II interrupted whaling and some whale populations temporarily increased. The moratorium signed in 1982 by the International Whaling Commission prohibited further whaling, and some populations are rebounding. From Jennings *et al.* (2001, p. 14). Reproduced with permission of John Wiley & Sons.

et al., 2005). And due to illegal, unreported, and unregulated (IUU) fishing and related activities, often encouraged by corrupt practices, fisheries statistics underestimate total removal (FAO, 2012), threatening efforts to secure long-term sustainable fisheries (Fig. 2.8). The ever-growing demand for fish drives many fisheries to exploit natural populations beyond the capacity of fishes to replenish themselves and for ecosystems to recover from loss. Most fisheries are fully exploited (Fig. 2.9), overfishing continues, collapses are accelerating (Worm *et al.*, 2006), and major ecological disturbances are evident (Pauly and Christensen, 1995; Jackson *et al.*, 2001). Few areas of the world remain unexploited, and few are protected from fishing; recovery when and if it occurs can be slow. To offset the declining capture fisheries, increasing aquaculture production aims to fill the ever-rising need for more food (Fig. 2.10; FAO, 2010).

The drama in fisheries over-exploitation has historical roots, exacerbated by improved efficiencies. Fisheries have moved from one location to another in a *slash-and-burn* pattern of exploitation, exploiting areas where the harvestable biomass is greatest, fishes are most accessible, or both (Law, 2000). North Atlantic fish depletions began in the late 1800s with plaice (*Pleuronectes platessa*, a European flatfish) followed by Atlantic herring (*Clupea harengus*), Atlantic cod (*Gadus morhua*), and other fisheries in the 1900s (Holt, 1969). Four centuries of

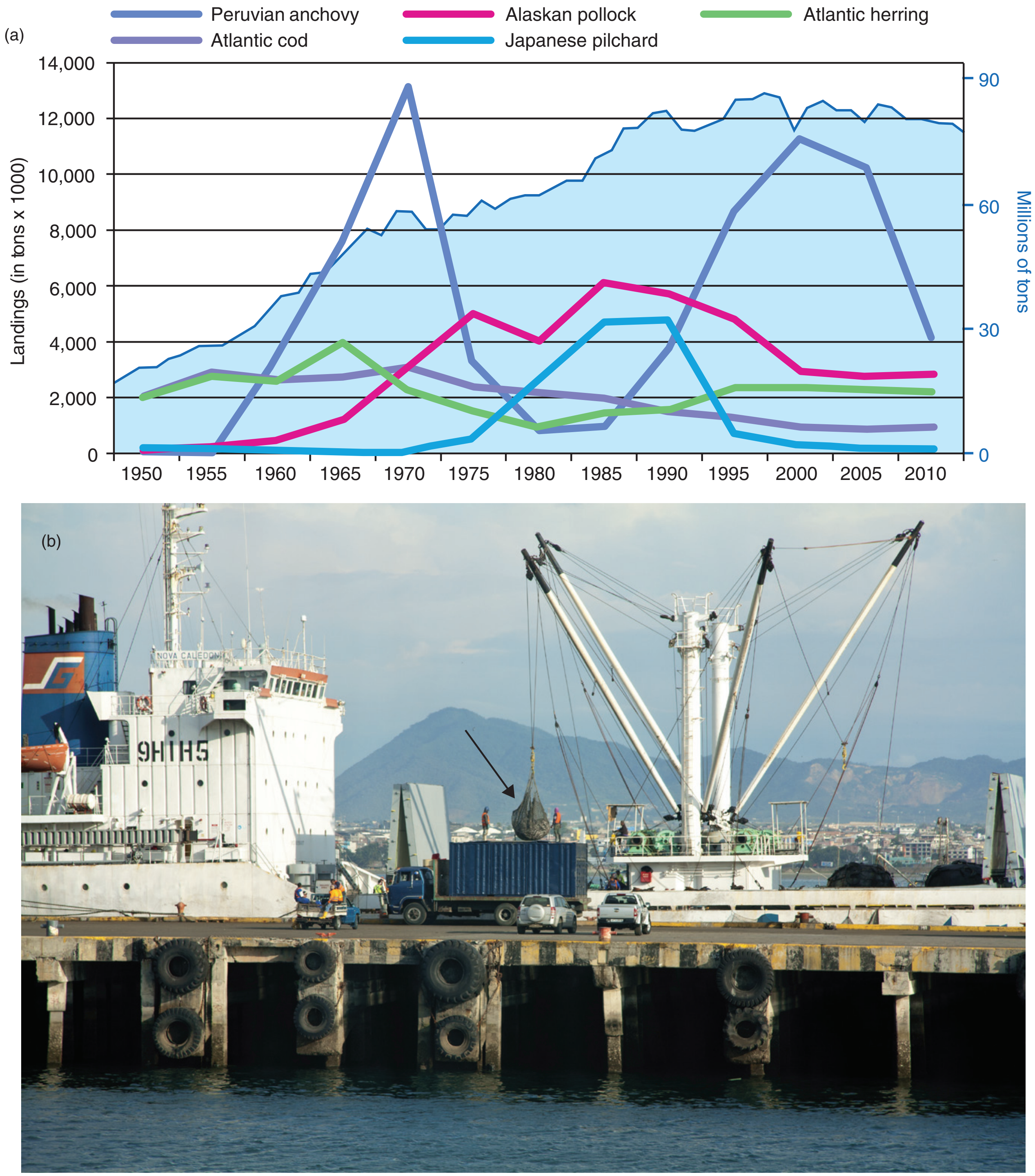

Fig. 2.7 Major fisheries extractions from global oceans. (a) World fisheries landings increase since 1950. Total marine fish landings (right ordinate; data from FAO, 2012) and individual landings (left ordinate) for five high seas marine fish species that dominate global landings: Peruvian anchovy (*Engraulis ringens*); Alaskan pollock (*Theragra chalcogramma*); Atlantic herring (*Clupea harengus*); Atlantic cod (*Gadus morhua*); Japanese pilchard (*Sardinops melanostictus*). Based on data in FAO Fisheries and Aquaculture Information and Statistics Service—06/08/2012 online (2012): www.fao.org/fishery/statistics/global-production/en. (b) Tons of albacore tuna (*Thunnus alalunga*) being loaded from a factory fishing ship (arrow) into truck in Manta, Ecuador (May 2012), where the tuna industry is the largest city employer. Photograph © Charles Clarkson.

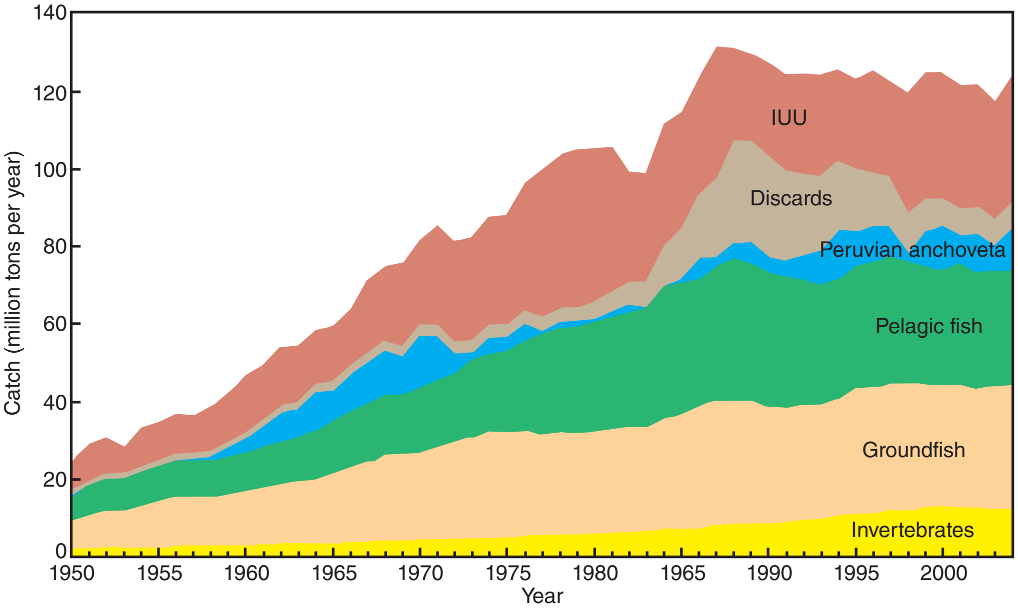

Fig. 2.8 Total extraction of marine fisheries from 1950–2004, which accounts for over-reporting by China, discards of bycatch and other discards, and Illegal Unreported or Unregulated (IUU) extractions. Such IUU fishing occurs in virtually all capture fisheries, valued at an estimated $10–23.5 billion per year (FAO, 2010). From Pauly 2008. Reproduced with permission from Sea Around Us.

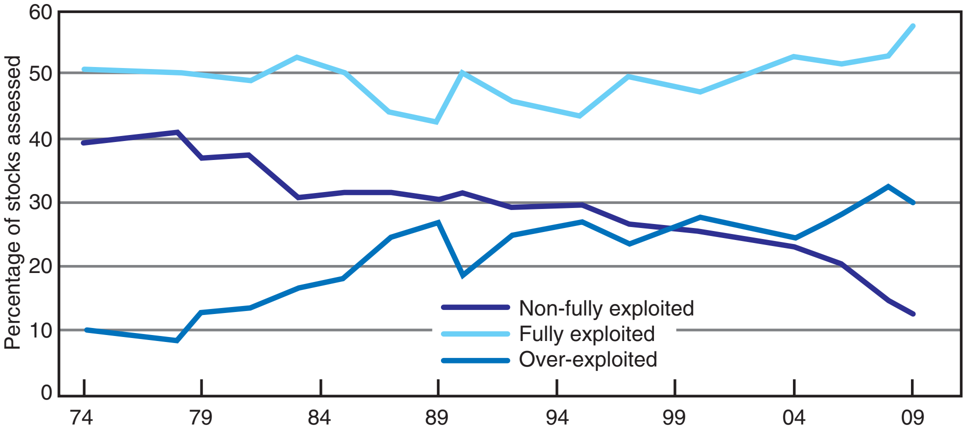

Fig. 2.9 Trends in world marine fisheries indicate that ocean fisheries production is approaching global capacity. Global assessment of fisheries stocks since 1974 indicated that the proportion of non-fully exploited stocks gradually decreased as the percentage of over-exploited stocks increased, especially late 1970s and 1980s. From Food and Agriculture Organization of the United Nations (2012). *The State of World Marine Fishery Resources*. FAO Fisheries and Aquaculture Department. Food and Agriculture Organization of the United Nations, Rome. www.fao.org/docrep/016/i2727e/i2727e00.htm

overfishing Atlantic cod that intensified after World War II forced its collapse in the 1990s and devastated coastal economies (Hutchings, 2005). With technological improvements (Thurstan *et al*., 2010) and larger, more numerous vessels with greater efficiency after the War, fishing efforts rapidly expanded. Today, about 4.3 million large fishing vessels and increasing numbers of small, unaccounted fishing boats are actively pursuing fish, accompanied by much under- and over-reporting (FAO, 2010). These vessels are being equipped with efficient fish-finding devices and navigational aids that pinpoint fishing grounds. Lloyd's 2005 register of ships greater than 100 tons accounted for about 1200, with increasing numbers of flag-state registrations being listed as *unknown* (Gianni and Simpson, 2005), and contributing increasingly to widespread and profitable IUU fishing impacts (Flothmann *et al*., 2010). Vessels are using 2 km-long drift nets and longlines that extend tens of kilometers with thousands of hooks that fish indiscriminately. Factory ships meet fishing vessels at sea to efficiently process loads of fish for markets (Fig. 2.7b). This massive removal of more fish is accompanied by increasing numbers of countries failing to report landings, inappropriately reporting catches, and/or engaging in illegal

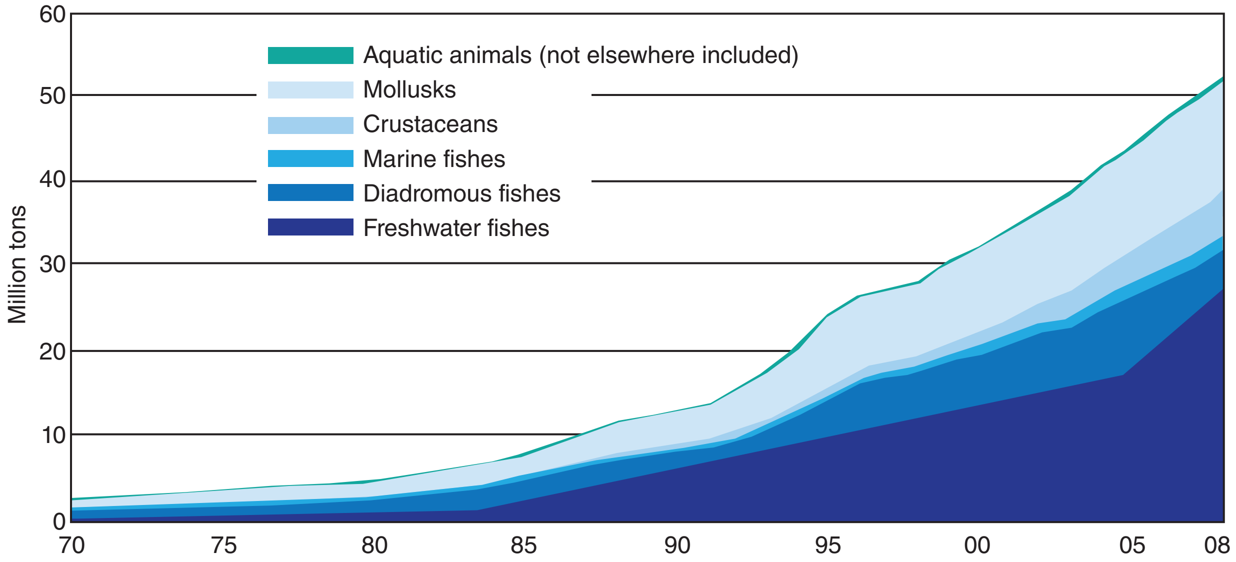

Fig. 2.10 World aquaculture production reflects increasing market demand since 1970 for major fisheries groups, especially mollusks (oysters, mussels, clams) and crustacea (shrimp, lobster, crabs), which supplements capture fisheries and accounts for almost half of total food fish. Aquaculture is the fastest-growing animal-food-producing sector and a major source of income and livelihood for hundreds of millions of people. From Food and Agriculture Organization of the United Nations (2012). *The State of World Marine Fishery Resources*. FAO Fisheries and Aquaculture Department. Food and Agriculture Organization of the United Nations, Rome. www.fao.org/docrep/016/i2727e/i2727e00.htm

trade. Fishing now extends into the deep sea where impacts are poorly known (Davies *et al*., 2007). Ocean fisheries production is approaching global capacity (Garcia *et al*., 2005; NRC, 2006; FAO, 2012). Furthermore, highly efficient fishing methods have greatly increased captures of non-targeted species (bycatch; discards), including cetaceans, seals, sea turtles, sharks, tuna, sea birds, and juvenile fishes. The amount of bycatch, estimated at about 20% of the total, is difficult to estimate due to lack of reporting (Fig. 2.8); discards in tropical shrimp trawl fisheries alone may be orders of magnitude greater than the retained catch (Zeller and Pauly, 2005).

Benthic trawling is an expansive and variably damaging operation that adds another dimension to fishery impacts (Gray *et al*., 2006). Extensive trawling occurs on the northeast Atlantic shelf (Kaiser *et al*., 1998), southern North Sea (Rijnsdorp *et al*., 1998), and elsewhere; some areas are completely dredged three to four times per year. Trawling and dredging can reduce biodiversity, cause serious ecological impacts (Thrush and Dayton, 2002), and can restructure benthic environments (NRC, 2002a). Dredges are used in estuarine waters to harvest clams, oysters, conch, and crabs, and in offshore waters to harvest sea scallops, surf calms, and quahog clams. Trawling grounds of 24 countries encompass more than 57% of global continental-shelf area, covering 8.8 million km^2 (Burke *et al.*, 2001). The effects are increased turbidity, alteration of benthic habitats, crushing, burying, and smothering biota, and subjecting non-targeted sessile species to predation. In comparison to forest clearcutting, modern trawling is globally 150 times more expansive (Table 2.1).

Marine ecosystems are further affected by extractions of targeted species for aquarium and ornamental species trade, a $25 billion-per-year worldwide industry that is growing at 14% per year (Padilla and Williams, 2004). This trade involves 1471 species of fish and more than 500 invertebrate species, including 140 stony corals and millions of individuals. Over-harvesting of precious corals follows a sequence similar to fisheries: i.e., exploration, discovery, exploitation, depletion (Wabnitz *et al*., 2003). And while trade is legitimate, illegal trade is a growing ecological and management concern. Between 2003 to 2006, for example, up to 1.05 million Caribbean queen conch (*Strombus gigas*), a marine mollusk valued for its shell in the ornamental trade, were illegally harvested, with a conservative estimate of more than $2.6 million in value (Daves, 2009). This adds to the total impact of biomass removal, with consequences for biodiversity and marine ecosystem function (Donaldson *et al*., 2010), and involves complex issues of management, ecosystem impact, and social justice (FAO, 2010).

2.3.1.2 Minerals

The marine environment is a distinct geological province (Mangone, 1991), a hotbed for mineral extraction with active sources of mineralization occurring along plate boundaries (Rona, 2008; Rona, 2003). Salt, magnesium, and bromine are recovered from seawater; rock, coral, calcareous marls, shells, sand, gravel, and lime used for coastal protection, beach replenishment, industrial construction, etc., are commonly extracted from beaches and the seabed (UN-ISA, 2004). Phosphorite is mined from salt marshes for fertilizer and offshore

Table 2.1 Comparison of impacts: forest clear-cutting and benthic trawling. Watling & Norse 1998. Reproduced with permission of John Wiley & Sons.

Impact on:	Forest clear-cutting	Bottom trawling/dredging by fishing gear
Substrate	Exposes soils to erosion; compresses soils; loss of nutrients	Overturns, moves, buries boulders/cobbles; homogenizes sediments; eliminates microtopography; leaves long-lasting grooves; alters nutrient flux
Roots and infauna	Saprotrophs (that decay roots) are stimulated then eliminated	Infauna crushed and buried; others become susceptible to scavenging
Biogenic structures	Removes above-ground logs; buries structure-forming species; simplifies habitat	Removes, damages, displaces structure-forming species/habitat, e.g., seagrass, oyster beds; simplifies benthic habitat
Cascading effects	Eliminates most late-succession species; encourages pioneer species	Eliminates most late-succession species; encourages pioneer species
Biogeochemistry	Releases large carbon pulse to atmosphere by removing and oxidizing accumulated organic material; eliminates arboreal lichens that fix nitrogen	Releases large carbon pulse to water column and atmosphere by removing and oxidizing accumulated organic material; increases oxygen demand
Recovery time to original structure	Decades to centuries	Years to centuries; variable, depends on size, duration, frequency
Typical return time	40–200 years	40 days to 10 years
Global area affected per year	~0.1 million km^2 of net forest and woodland loss	8.8 million km^2
Latitudinal range	Subpolar to tropical	Subpolar to tropical
Ownership	Private and public	Public
Scientific documentation (publications)	Many	Well documented
Public awareness	Substantial; visual impact	Very little; obscure, out-of-sight
Legal status	Modify activity to lessen impacts; prohibit or favor alternate logging methods and preservation	Fisheries management; restricted activity for few areas

coal deposits are extracted by tunneling from shore out to sea. Throughout Southeast Asia, large quantities of tin and its mineral cassiterite are dredged from shallow offshore waters. Shores also contain many high-value, low-volume minerals, e.g., platinum, gold, silver, titanium, zirconium, chromium, and rare-earth minerals; gold-bearing sands and gravels buried in fluvial channels are dredged in the shallow offshore waters of Alaska, New Zealand, and the Philippines. Diamonds are dredged from the seabed in water up to 200 m deep in Namibia and South Africa. Mining has a long history of dumping waste into nearshore areas, with very damaging effects, as for example at Placer Dome's Marcopper mine in the Philippines (Coumans, 2003).

Mining contributes significantly to the global economy, with risks and conflicts over its potentially lucrative future. As many mineral resources are located on continental margins and in the deep sea, geopolitics and uncertainties over national jurisdictions come into play (UN-ISA, 2004). Once resolved, greater certainties over ownership will open doors to deep-sea mining for manganese nodules; nearly 70% of the deep-sea floor at depths below 4000 m contains these small, golf-ball-size nodules. The deep sea also contains gas hydrates (350–5000 m depth), cobalt (1000–3000 m along undersea mountain ranges), and massive amounts of sulfides (500–4000 m near plate boundaries; Bollmann *et al.*, 2010). The extraction of almost all minerals produces considerable amounts of waste, much of which is toxic, and generates fine sediment plumes that may contain heavy metals that settle and suffocate benthic organisms at varying distances from the source.

2.3.1.3 Fossil fuel extractions: oil and gas

Oil and natural gas are key fossil fuel resources that power industrial societies. World oil consumption in 2007 reached about 3.9 billion tons a year and is expected to increase at least another 50% by 2030. As prices rise and deposits dwindle, energy demand will escalate offshore oil extractions for the greatest consumers: USA, China, and Russia (Bollmann *et al.*, 2010). The ecological consequences of accidents are acute, chronic, and highly variable (Peterson *et al.*, 2003).

Oil and gas lie under vast layers of ocean-floor sediments. Of a worldwide estimate of 157 billion tons of easily obtainable oil, 26% comes from offshore sources, an extraction that is growing more strongly than onshore (Bollmann *et al.*, 2010; Fig. 2.11). By 2012, 17 giant offshore fields are expected, each containing at least 500 million barrels of recoverable oil, with drilling operations moving into deeper water depths and into more hazardous areas (Robelius, 2007). Within five years,

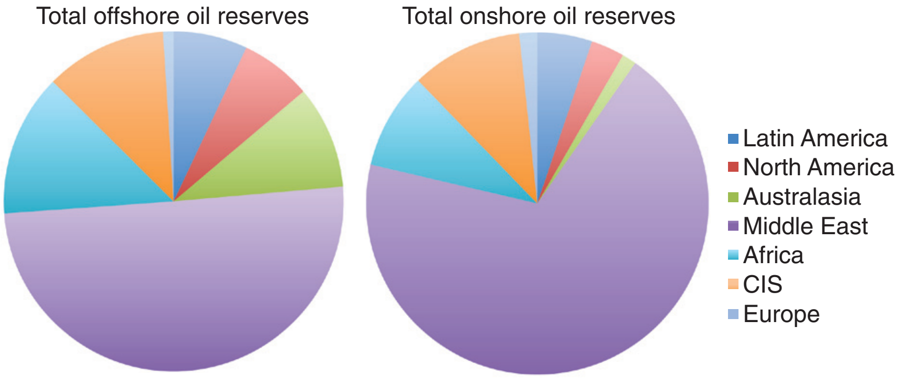

Fig. 2.11 Relative comparisons of conventional onshore and offshore oil reserves by geographic region in 2007. From onshore and offshore combined estimated total of 157 gigatons (Gt) of oil reserves, Bollmann estimates that 26% (4 Gt) or more comes from offshore and deep-water sources. An estimated 30% of undiscovered gas and 13% of undiscovered oil in the marine areas occur north of the Arctic Circle, mainly in Russian waters. CIS = Commonwealth of Independent States. Based on data from Bollmann *et al*. (2010).

Cambridge Energy Research Associates expects global deep-water production to extract the equivalent production of Saudi Arabia—an estimated 10 million barrels a day from the most productive offshore areas: North Sea, Atlantic Ocean off Brazil, West Africa, Gulf of Mexico, Arabian Gulf, and seas off Southeast Asia. The Gulf of Mexico now produces 91% of offshore oil/gas extraction, followed by the relatively shallow North Sea (average depth 40 m) whose production is declining, followed by the Arabian Gulf, and Southeast Asia seas. The offshore areas of India, South China Sea, and Caspian Sea (off Kazakhstan) are emerging as major fields. In the U.S. over the past two decades, about one-quarter of its total natural gas production came from offshore sources, yielding almost 30% of the total oil production (Office of Oil and Gas, 2005). An estimated 30% of undiscovered gas and 13% of undiscovered oil is in the Arctic Ocean, a vulnerable region. Extraction of oil and gas in high-latitude seas is subject to sea ice and harsh winter storms, where spill clean-up presents technological challenges yet to be resolved. Similarly, drilling in areas prone to earthquakes, hurricanes, and tsunamis is technologically hazardous, as in areas of the Western Pacific and elsewhere.

2.3.1.4 Extracting ocean energy

Coastal waters potentially provide plentiful and predictable renewable, clean energy (Pelc and Fujita, 2002). Wind, waves, and currents contain about 300 times more energy than humans are currently consuming, and power plants are converting ocean energy into electricity (Bollmann *et al*., 2010). Worldwide, about 40 offshore wind energy projects have been implemented, mostly in the United Kingdom, Denmark, the Netherlands, and Sweden, with facilities becoming bigger and venturing into deeper waters. However, although renewable energy generators may be relatively environmentally clean, they have their own set of problems, for example, adding human activity, vibration, and underwater noise to the marine environment, with poorly known consequences for marine life.

2.3.2 Introductions: adding novelty to marine ecosystems

Humans continually add new products to the ocean's chemical soup. These include synthetic chemicals, toxic metals, trash, radioactive materials, pathogens, pesticides, exotic species, artificial heat, noise and light, nutrients, disease agents, and endocrine-disrupting compounds, added slowly and chronically, or suddenly and in concentrated forms, but rarely in accord with natural rhythms. Watersheds and groundwater transfer pollutants and materials to coastal waters, ships discharge litter, waste, exotic species, and chemicals, accidentally or deliberately at sea (ocean dumping, bilge cleaning, antifouling paints). And from the air, storms, winds, and rain deliver debris, chemicals, nutrients, microbes, and others.

2.3.2.1 Adding nutrients to coastal waters

High crop yields and green lawns benefit from fertilizer applications. About 143 million tons are globally applied to land each year (FAO, 2005), and its use is increasing (Bumb and Baanante, 1996), adding high concentrations of nitrogen and phosphorous (Fig. 2.12), essential chemicals for life. Increasing quantities of anthropogenic fixed nitrogen are entering rivers, groundwater, and atmosphere (Duce *et al*., 2008), directly from wastewater treatment plants, sewage systems, and stormwater overflows, or indirectly via groundwater contamination, precipitation, and land runoff from farms, septic systems, lawns, streets, and roads.

2.3.2.2 Adding toxic petroleum and related byproducts

Roughly 1.4 billion liters of petroleum and related hydrocarbons enter the oceans annually, chronically in low doses and catastrophically in high doses (NRC, 2002c). Tanker accidents exceeding one thousand barrels account for most of the world's oil spills, but chronic exposures from daily releases (accidental, illegal) occur regularly. A city of five million people, for example, might annually release roughly the equivalent of the tanker *Exxon Valdez* oil spill, the difference being that a city's input is chronic whereas an oil spill is acute.

"Petroleum" is a broad term that describes naturally occurring and refined compounds of oil and natural gas, with toxic qualities that vary with degree of industrial refinement (NRC, 1985). Petroleum from natural (e.g., submarine seeps) and anthropogenic (tanker accidents, ship deballasting operations, etc.) sources contains varying degrees of benign and toxic properties. Unrefined crude oil is a widely varying hydrocarbon

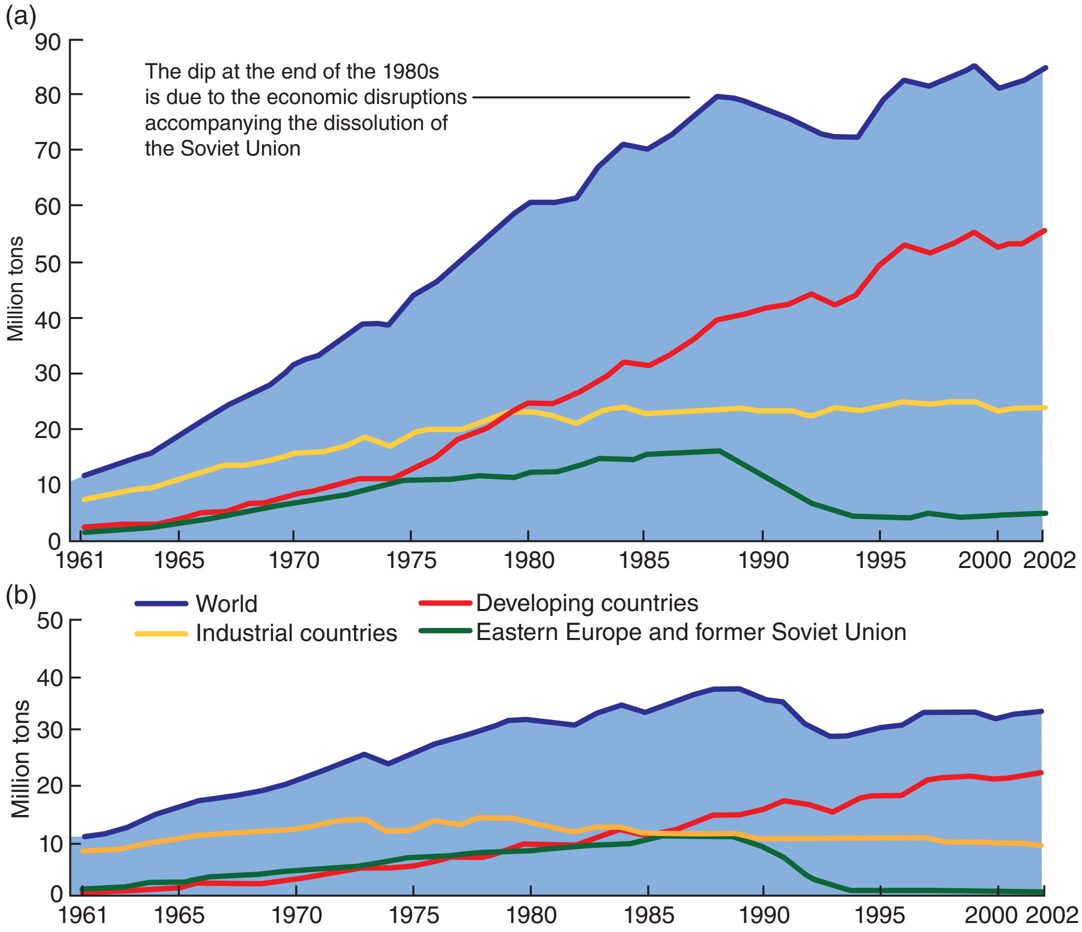

Fig. 2.12 Regional, global, and country trends in use of fertilizers, 1961–2001. Nitrogen and phosphorous are key fertilizers used globally to increase food production and are degrading water quality. (a) Increased applications of synthetic production of nitrogen fertilizer and other uses of nitrogen. (b) A steady threefold increase in use of phosphate occurred until 1990, then banning use decreased its levels to about equal to 1980 applications. Nitrogen and phosphate pollution enriches freshwater ecosystems, creates hypoxia in coastal marine ecosystems, and contributes to nitrous oxide emissions contributing to global climate change and air pollution in urban areas. From Millennium Ecosystem Assessment (2005), www.wri.org.

compound that contains a complex mixture of some toxic chemicals and heavy metals with a variety of sticky and persistent properties. Refined petroleum, in contrast, contains high concentrations of soluble, highly toxic components (e.g., benzene, toluene, xylene) in acute exposures that can quickly evaporate. Due to oil pollution, toxic arsenic concentrations are increasing in the ocean (Wainipee *et al*., 2010).

Polynuclear aromatic hydrocarbons (PAHs), mostly from incomplete combustion of fossil fuels, pose potential hazards to humans and sea life. PAHs are ubiquitous compounds from such human activities as industrial effluents, domestic sewage, oil spills, bilge water, and creosote on dock pilings that are released into the air, transported in particulates, and precipitate to the ocean surface. The heavier, more persistent PAHs, e.g., carcinogenic benzo(a)pyrene that can concentrate in organisms, especially shellfish, have greater carcinogenic potential. Bottom-dwelling fish exposed to chronic PAHs in harbors have lesions and deformities.

The risk of oil spills is increasing worldwide. For several decades, oil companies have been venturing into deeper waters, and waters subject to harsh weather and environmental conditions. A major oil field offshore of Russia's eastern Sakhalin Island (Sea of Okhotsk) is subject to severe earthquakes, storms, and sea ice, where spills are a potential threat to the dwindling western North Pacific population of endangered gray whales (*Eschrichtius robustus*) and to indigenous people. In the Arctic today, major oil companies are seeking leases and building infrastructures to tap into rich oil deposits, venturing into hazardous conditions in areas that are also critical habitat for marine mammals.

Large-volume spills have increased since the 1950s (Table 2.2). Spills from large, out-of-control wells are infrequent, but they are massive. The earliest in the U.S. occurred off Oregon coast when the tanker *Mandoil II* released about 314,000 barrels into the Pacific Ocean. In 1979–80, the exploratory well *Ixtoc*, with a subsurface drill depth reaching 3600 m,

Table 2.2 Major ocean oil spills. Compiled from Clark (1997); Irwin *et al*. (1997); World Almanac Books (1998); NOAA (2012), online Incident News.

Date	Location	Source	Amount in barrels (x 1000)	Cause
1967	Atlantic Ocean (Scilly Isles, UK)	*Torry Canyon*	860	Grounding
1968	Pacific Ocean (Oregon)	Mandoil II	314	Tanker collision
1969	Pacific Ocean (Santa Barbara, Calif)	*Alpha Well 21 Platform*	103	Well blowout
1970	Pacific Ocean (Bermuda)	*Chrissi*	235	Tanker structure
1976	Atlantic Ocean (Nantucket, Mass.)	*Argo Merchant*	183	Grounding
1977	Pacific Ocean (Hawaii)	*Hawaiian Patriot*	95	Tanker fire
1978	Atlantic Ocean (Brittany, France)	*Amoco Cadiz*	1 600	Grounding
1979	Atlantic Ocean (West Indies)	*Atlantic Empress*	2 124	Tanker Collision
1979	Gulf of Mexico (Mexico)	IXTOC I	3 500	Wellhead blowout
1980	Niger Delta (Nigeria)	Funiwa No 5 Well	200	Well blowout
1983	Atlantic Ocean (South Africa)	*Castillio de Bellver*	1 870	Tanker fire
1988	Nova Scotia (Canada)	*Odyssey*	968	Tanker explosion
1989	Prince William Sound (Alaska)	*Exxon Valdez*	275	Grounding
1991	Arabian Gulf (Kuwait)	Iraq bombing	11 000	Gulf War
1991	Atlantic Ocean (Angola coast)	*ABT Summer*	1 920	Tanker explosion
1991	Mediterranean Sea (Italy)	*MT Haven*	1 140	Tanker fire
1993	Atlantic/North Sea (Shetland Islands)	*MV/Braer*	623	Heavy weather
1994	Arctic (Russia)	*Usinsk*	765	Pipeline rupture
2002	Atlantic O. (Galicia coast, Spain)	*The Prestige*	576	Aging tanker
2005	Gulf of Mexico (US)	Hurricane *Katrina*	190	Hurricane
2010	Gulf of Mexico (US)	*Deepwater Horizon* oil rig	4 900	Platform explosion

released about 3.3 million barrels of crude oil for 290 days into Bay of Campeche, Mexico (Jernelöv and Lindén, 1981). In 1989, the *Exxon Valdez* released about 275,000 barrels of crude oil into Prince William Sound (Alaska) that spread more than 900 km westward to contaminate shores and subtidal sediments. Many species have still not recovered, and recovery for orcas has been especially slow (Matkin *et al*., 2008). In 2005, Hurricane Katrina spread 190,000 barrels of crude and refined oil products into the Mississippi River and Gulf of Mexico, followed in 2010 by the *Deepwater Horizon*, the world's largest oil spill outside of war. The *Deepwater Horizon* platform exploded and caught fire on April 20 2010 in the northern Gulf of Mexico. It released about 4.9 million barrels during 86 days from its ultra-deep 1500 m well (Cleveland *et al*., 2011) that spread across about 75,000 km^2 to pollute offshore waters, lagoons, sandy beaches, and barrier islands. The oil affected a variety of sea life (some endangered, Campagna *et al*., 2011), wetlands, shellfish reefs, and deep-benthic habitat; these impacts are still being felt, for example on marshes and other wetlands, further exacerbated by multiple human causes (Silliman *et al*., 2012). Concentrated toxins and tons of methane gas contaminated one of the world's most productive ecosystems, probably for years to come. Scientists most often lack critical data to predict ecological consequences (Bjorndal *et al*., 2011), but as the *Exxon Valdez* disaster proves, the persistence of toxic and sublethal exposures may affect wildlife long after the acute phase ends (Peterson *et al*., 2003; Chen and Denison, 2011).

2.3.2.3 Adding persistent bioaccumulative toxins (PBTs)

Coastal waters receive many highly toxic substances in common use, and that are extremely persistent. Some are endocrine disrupters that can cause reproductive or nervous system dysfunction, behavioral abnormalities, and birth defects. Many are carcinogenic and more are lethal or sublethal in effect. PBTs are primarily synthetic chemicals designed and manufactured to meet a wide range of industrial, agricultural, residential, and personal needs (Table 2.3). Integral to PBTs are persistent organic pollutants (POPs), which include trace metals and organo-metal compounds. PBTs released into the environment generally resist physical, chemical, and metabolic breakdown and accumulate in sediments near industrial or urbanized areas, where organisms feed. The toxin concentrates in the fatty tissues of marine organisms; over time the body-load can reach a magnitude greater than ambient seawater, such that the organisms themselves become toxic (Fig. 2.13). Among the most contaminated are marine mammals, especially orcas (Hickie *et al*., 2007); one dead individual washed up on a Pacific Northwest shore had a PCB body burden of such magnitude to be declared toxic waste!

PBTs are ubiquitous and persist despite commercial bans and regulated use. They are emerging in the Arctic in high enough concentrations to affect wildlife and people (Muir and de Wit, 2010). They include PAHs, e.g., halogenated aromatic hydrocarbons (e.g., organochlorines), polychlorinated biphenyls

Table 2.3 Acute and persistent anthropogenic toxins harmful to sea life.

TOXIN TYPE	SOURCES	BIOLOGICAL IMPACT
Heavy metals:	**Industrial concentrations of naturally occurring. Ubiquitous.**	**Interacts with biomolecules; impact varies with marine species and organ; liver is great accumulator.**
Cadmium	Industrial production into products; from mines, rivers, atmosphere, dredging	Collects in inshore mud flats, bacterial films, and organic matter
Copper	Electrical industry alloys; electrical wiring, algicides, acid mine drainage	Essential in biochemical processes; catalyst in hemoglobin formation; highly toxic to invertebrates
Mercury	Power plants; pulp/paper mills, fungicides, fossil fuel combustion, mercurial catalysts, weathering	Natural bacteria convert mercury to methylmercury that concentrates in fish, bioaccumulates; endocrine disruptor; toxic if eaten
Tin	Organotin production for pesticide, PVC stabilizer, biocide, etc. increased from 5000 tons in 1995 to 35,000 tons in 1985; now ~ 50,000 tons	Damages marine life worldwide. Tributyltin is extremely toxic to oysters. Sediment microorganisms convert metallic tin into methyltin
Zinc	Sewage/industrial discharge. Used in alloys, paints, cosmetics, etc. to coat steel/iron against corrosion, roofing	Catalytic activity essential in biochemical processes. Most toxic to aquatic microscopic organisms; larvae
PBT, POP: ***Persistent***	**Industrial organic synthetics**	**Many are lipophilic. Can be carcinogenic, mutagenic, endocrine disrupter**
DDT, DDE, DDD	Organo-pesticides, extensively used	Sediment; lipophilic, bioaccumulate, hormonally active
Chlordane	Ubiquitous pesticide 1948 to 1978	Bioaccumulate in sea life (marine mammals, sea turtles)
Octachlorostyrene	Waste byproduct from chlorine production prior to 1970	Suspected endocrine disruptor. Concentrates in sediments, sea life, marine mammals, dead cormorants
Mirex	Chlorinated pesticides, used extensively	Persistent. Concentrates and chronically toxic to sea life
Polyaromatic hydrocarbons (PAHs)	Crude oil, refined oil, aerosols; sewage; surface runoff. Widespread	Low water solubility. Concentrates in sediment, biomagnify: benzo(a)pyrene is a carcinogen and endocrine disrupter.
Polychlorinated biphenyls (PCBs)	Dielectric fluids in electrical equipment (transformers, hydraulic systems); sewage; widely distributed	Highly persistent; concentrates in sediments, liver, gonad, sea turtles
Dioxins (2,3,7,8-TCDD)	Unintentional byproducts of combustion and industrial chemical processes; from incineration, pulp/paper production	Among the most toxic: occur in seafood: affect food webs, carcinogenic, endocrine disrupter
Recent concerns		
Polybrominated diphenyl ethers (PBDEs)	Flame retardants used in plastics, foams, fabrics etc., important to human safety; exponential increase since 1970s	Persistent; disperse globally to deep ocean water, polar regions; in sediment, soil; concentrate/biomagnifies in sea life; fetal toxicity; teratogenicity; mass mortality; marine mammals; seabirds
Pharmaceuticals/ personal care products (PPCPs)	Prescription, over-counter therapeutic drugs, veterinary drugs, fragrances; cosmetics; in sewage, from industry	Mostly unknown. Antibiotic resistant; subtle, insidious effects; bioaccumulative potential

(PCBs) from plastics and electrical equipment, and pesticides being added at more than 5.0 billion pounds to land each year (Fishel, 2007). Pesticides can cause unexpected and unintentional harm to many invertebrate marine species that are essential to food-web transfer. The organochlorines are of most concern, e.g., DDT (dichloro diphenyl trichloroethane) and its derivatives DDE (dichloro diphenyl ethane) and DDD (dichloro diphenyl dichloroethane); these were banned or phased out from use internationally by the Stockholm Conference (Ch. 3), but persist in the environment to affect immune and nervous systems of organisms. PCBs are stored in sediments and bioaccumulate and biomagnify up food chains to cause tumors, fetal death, and birth defects in various species. Dioxins, the byproducts of chlorinated substances used to bleach paper pulp, are extremely toxic, persistent, and can cause abnormalities and tumors. Newer PBTs in current use and entering aquatic systems include brominated flame retardants and numerous pharmaceutical and personal care products (PPCPs) for which the impact is little known (SCCWRP, online). PBTs and hundreds or thousands of other toxics entering coastal/marine waters are mostly not monitored, and generate concerns for their cumulative and increasing impact on coastal ecosystems (Dachs and Méjanelle, 2010) and on people. Due to bioaccumulation, the highly toxic organic form of mercury (methyl mercury) raises serious concerns about seafood consumption safety for humans (Fitzgerald *et al.*, 2007), as first witnessed in Minimata (Japan) in 1956 that caused severe neurological damage to many people.

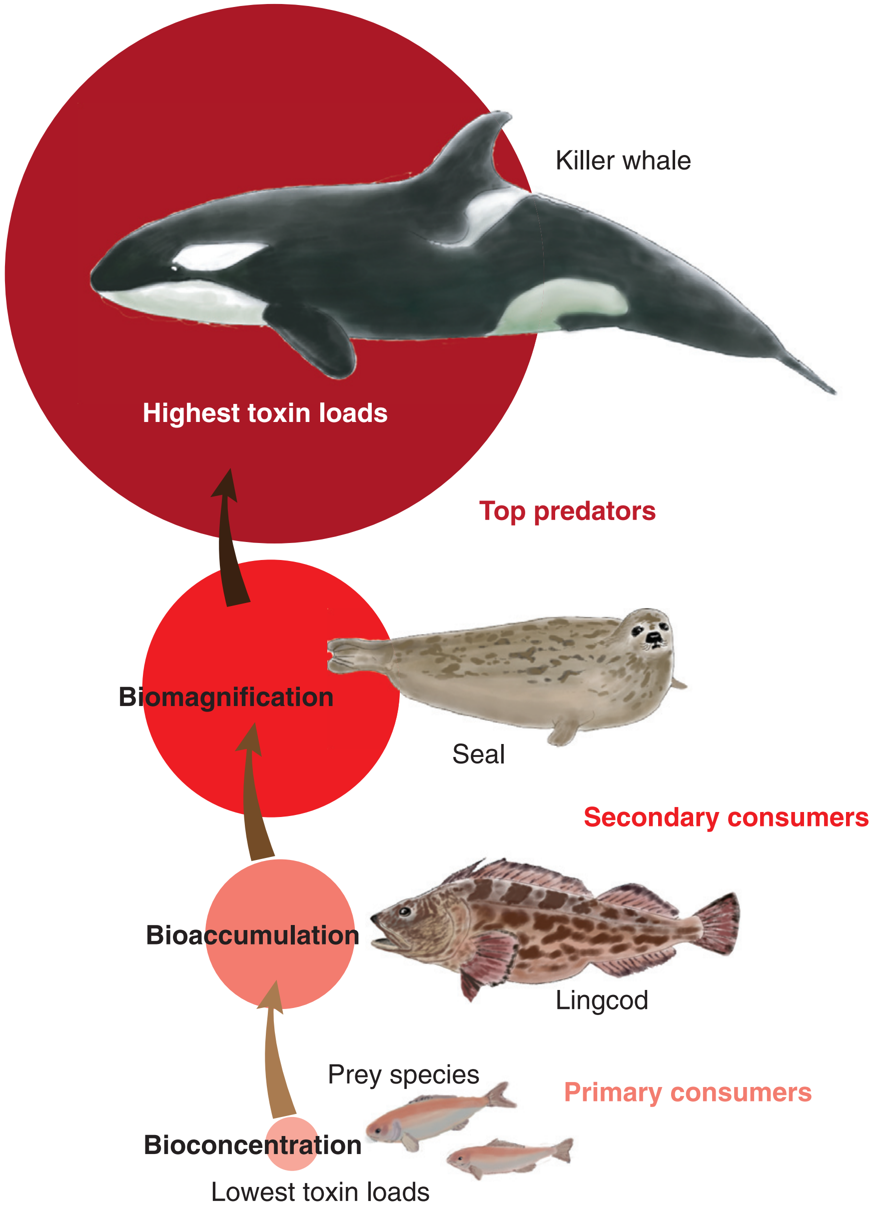

Fig. 2.13 Biotoxicity. Toxic accumulations in organisms are made worse by human activities. Biotoxicity results from feeding on contaminated food that becomes transferred and accumulated up the food chain: from bioconcentration (concentration of toxin in an organism, not through food web) in primary consumers; to bioaccumulation (biological sequestering of toxin at higher concentration than environment) in secondary consumers; to biomagnification (biological transfer of a toxin amplified up through trophic levels of food web). Organisms at high trophic levels (e.g., orcas, humans) are often exposed to high concentrations of toxic chemicals, e.g., persistent organic pollutants (POPs). USGS, online definitions. Data from Ross and Birnbaum (2003).

2.3.2.4 Adding litter and persistent plastics

Marine litter occurs in all oceans, accumulating along shores and in water, both in densely populated regions and remote places far from obvious sources and human activities (Fig. 8.28). Most litter is accidentally or carelessly released, although many commercial, fishing, metropolitan, and military disposal operations purposefully introduce tens of thousands of tons of litter annually into the seas. The North Pacific Subtropical Gyre, called the “Garbage Patch” (Kaiser, 2010), draws attention to the poorly quantified deaths of thousands, even millions, of marine mammals, seabirds, sea turtles, and fishes every year (NOAA, online). Introduced materials profoundly alter feeding behavior of animals. Sea turtles, seabirds, and marine mammals are especially likely to ingest foreign objects, and each year many thousands may be injured, receive inadequate nutrition, or die due to digestive-system blockage.

Plastics are a dominant component of ocean litter. Globally, its production increased from 1.5 million tons in 1950 to 230 million tons in 2009, resulting in durable and serious toxic and mechanical effects (Gregory, 2009; Hirai *et al.*, 2011). Plastic litter ranges in size from micro-millimeter particles (human body washes, cosmetics) to large objects, including abandoned fishing gear (e.g., buoys, fishing line, nets). The amount entering the oceans from all sources is staggering. Trawls regularly retrieve plastics and other debris, even from the deep sea. Especially serious are lost or discarded fishing gear (Fig. 2.14a). Tens of thousands of plastic fish traps lost at sea continue to “ghost fish” for long periods of time. Floating plastic sheets may cling to plants, corals, and intertidal

Fig. 2.14 Unintentional impacts by humans on coastal animals. (a) Steller sea lion (*Eumetopias jubatus*) skeleton entangled in discarded fishing gear on Amak Island, southeastern Bering Sea, 1974. The skeleton shows signs of having been consumed by a predator, probably a grizzly bear. Photograph © Ray & McCormick-Ray. (b) Porpoise (*Phocoena phocoena*) with propeller wounds found stranded in San Francisco Bay, California. Courtesy of The Marine Mammal Center, Sausalito, California.

animals. And thousands of exposed animals are trapped, smothered, strangled, entangled, killed, or deformed, while others suffer malnourishment and die slowly. Furthermore, small plastic fragments consumed by fish, larvae, and small organisms may contain toxic chemicals (PCBs, PAHs, DDTs, PBDEs, alkylphenols, bisphenol) that are endocrine disrupters (chemicals that interfere with endocrine or hormone systems of animals and people), and that can also bioaccumulate and biomagnify through food webs.

2.3.2.5 Adding harmful species

Humans regularly introduce pathogenic microbes and exotic species into new locations, where they may become extremely abundant and invasive. Some pathogenic and antibiotic-resistant microorganisms are introduced from human sewage systems, despite treatment. The common sewage bacterium *Serratia marcescens*, for example, is devastating Caribbean elkhorn corals (Sutherland *et al.*, 2011). Ships, too, have introduced pathogenic bacteria through routine discharge of ballast water, e.g., cholera (*Vibrio cholerae*) and other species that have caused severe economic impact. Ballast water discharged from ships is also responsible for introducing the Japanese toxic dinoflagellate (*Gymnodinium catenatum*) into Australian waters, zebra mussels and European shore crabs into North America, and comb jellies into the Black Sea (see Section 2.2.2). Precautionary measures of pumping bilge water into holding tanks and providing treatment at ports have been proposed, but are expensive and difficult to monitor; violations are frequent.

Entrepreneurs add cultivated, aquaculture fish in massive numbers to new locations. Worldwide demand for fish has dramatically spurred mariculture development since the early 1990s (Naylor and Burke, 2005). For some species (e.g., Atlantic salmon), global production has roughly quadrupled and now surpasses wild salmon fisheries. Successful Atlantic salmon farming encouraged aquaculturists to begin farming numerous other marine finfish, including depleted wild species, e.g., Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), Pacific threadfin (*Polydactylus sexfilis*), mutton snapper (*Lutjanus analis*), bronzini (*Morone labrax*), and bluefin tuna (*Thunnus thynnus*). Most are raised in coastal waters, but some are held in ocean net pens or cages. Serious local pollution often accompanies these facilities (Levin *et al*., 2001; Christensen *et al*., 2003; Krkošek *et al*., 2006).

2.3.2.6 Adding noise, heat, light pollution, collisions

The underwater world is getting noisier, for example for marine mammals that depend on sound for an acoustical image of their world (Weilgart, 2007; Box 2.4). Supertankers, huge fish-factory ships, cruise ships, military exercises, dredging and construction, oil exploration and production, fish finders,

Box 2.4 Noise pollution: a threat to dolphins?

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The significance of human-made sound in disturbing or injuring cetaceans has been considered only recently (Popper *et al*., 2000). Earlier studies of dolphin hearing were motivated by the discovery of the animal's sonar. Audiograms, plots of hearing threshold at different sound frequencies, have been done on several species of the cetacean superfamily Delphinoidea (narwhals, white whales, all dolphins, and the porpoises). The first detailed audiogram of the bottlenose dolphin showed especially good underwater hearing with a threshold of 42 dB re 1 μPa (10^{-14} W m^2) at 60 kHz. Studies also showed sensitivity to sound frequencies from about 60 Hz to 150 kHz, almost eight times the frequency span of human hearing (humans are slightly more sensitive to sound pressure in air, but our frequency range is limited to about 20 kHz).

Sensitive ears connected to a massive auditory central nervous system are fundamental to the dolphin's echolocation and communication. It is reasonable to ask how the animal, with such excellent hearing, avoids damaging its own ears with the loud sounds it produces during echolocation. The dolphin ear, anatomically only a few centimeters away from its sound production mechanism, processes high-frequency echolocation pulses up to 230 dB re 1 μPa in peak-to-peak amplitude. Using intense pulses and sensitive ears, dolphins can detect echoes (as quiet as a human whisper) from small objects at 100 m and more. Because the dolphin's pulses are very brief—on the order of 40 μs, and 25,000 of these would equal a second of sound, although the total energy within each pulse is minuscule. Anatomical structures, including highly reflective air sinuses that attenuate sound, probably help the animal avoid damaging its own ears.

On a comparative basis, the baleen whale auditory system does not appear as specialized as that of dolphins. The acoustic centers of the baleen whale brain are smaller than those of dolphins for whom the auditory nerve is the largest cranial nerve; the trigeminal nerve of the baleen is larger. Unlike dolphins, whose sense of hearing predominates, baleen whales appear to rely most on the sense of touch. Although we have made no audiograms, observations show that baleen whales usually produce low-frequency sounds often as low as 15 Hz.

If, as anatomical study suggests, the baleen whale ear is specialized for low frequencies, then the inference is that the animal's hearing is adapted to protection from considerable acoustic interference such as that which occurs from natural ocean background noise in the part of the acoustic spectrum below 1000 Hz. It is unlikely that baleen whales will be captured and trained for audiograms as have the delphinoids; nonetheless, physiological methods could be used to obtain audiograms on beached or entrapped whales.

The question arises: can baleen whales detect calls of other whales by means other than audition? The arrays of vibrissae about their heads suggest that baleen whales may use these adaptations to sense low-frequency vibrations, including the calls of other baleen whales. Uses of tactile detection like these may explain the large trigeminal nerve in baleen whales. Until audiograms can be measured on baleen whales, we are left to speculate about their hearing thresholds and frequency sensitivities. The absence of definitive audiograms compounds the problem of determining what levels of human-generated sound may damage baleen whale hearing.

Dolphins have evolved robust mechanisms to protect their ears and body tissues from loud natural sounds such as lightning strikes, earthquakes, pounding surf, volcanic eruptions, whale calls, and even their own echolocation pulses. Year after year, these adaptations are eroded as oceanic shipping raises the ambient background noise in the oceans. Intensified technology also introduces loud noise for purposes of improved sonar, oil exploration, and acoustic communication modems. These animals should not be continuously exposed to the equivalent of a boiler factory or even a loud discotheque. Increasing production of intrusive noise in the sea poses a serious threat to marine life. Science and technology must take action together in order to protect marine mammals such as dolphins and whales from dangerous noise.

depth sounders, speed boats, small watercraft, and submersibles that explore the deepest parts of oceans create a noisy presence. Also, the increasing presence of ships and recreational watercraft may result in collisions with sea life, inflicting serious injury or mortality. A major source of mortality for North Atlantic right whales (*Eubalaena glacialis*) has been collisions with large ships, a situation that has now been brought under partial control. But many smaller marine mammals are frequently killed or injured by collisions with recreational or small fishing boats, for example sirenians, seals, and porpoises (Fig. 2.14b).

Thermal pollution from industrial discharges changes ambient water temperatures, which can increase species' metabolism and affect ecosystems. Large amounts of heated water of more than 10°C above ambient sea temperature are released from industrial sources (e.g., power plants) into local waters. Elevated water temperatures also result from roads and parking lot drainage into urban and stormwater drains that ultimately discharge into nearby waters. Heat can differentially affect species' distributions and reproductive behavior; when levels are above a species' physiological tolerance, the impact can be lethal, most notably for tropical corals sensitive to temperatures >30°C. Elevated water temperatures also reduce oxygen saturation, exacerbating hypoxia.

The increasing extent and intensity of artificial night lighting near shores and at sea has substantial effects on wild species (Longcore and Rich, 2004). Artificial light from urban and seaside development disrupts marine bird and sea turtle navigation and orientation; sea turtle hatchlings emerging from sandy nests to scurry to the sea are disoriented and subject to predation where urban lights add a glow to dark shorelines. Lighted fishing fleets (Fig. 12.9), offshore oil platforms, and cruise ships bring artificial light to the world's oceans, potentially disrupting behavior patterns of many ocean species.

2.3.3 Physical alterations: structural changes of coastal systems

Humans constitute a massive geophysical force, globally transforming coastal land and sea for human uses, which causes major ecological change (Airoldi *et al*., 2005; 2009). Globally, humans have altered almost a third of coastal lands within 100 km of the coast (Burke *et al*., 2001) by physically transforming productive coastal-marine areas into urban/industrial complexes and by armoring the coasts against erosion and sea-level rise. Artificial structures now occupy more than half of the coasts of many nations; e.g., 1 km of coastline was developed every day in Europe between 1960 and 1995 (Airoldi and Beck, 2007). Along the northern Mediterranean coastline, urbanization, harbor, and port development now cover nearly 90% (e.g., French Riviera, Athens, Barcelona, Marseille, Naples, north Adriatic shorelines), with a projected increase of 10–20% expected for most shores.

2.3.3.1 Reclaimed land

Reclamation is most obvious in estuaries, lagoons, and shallow coastal waters, where millions of tons of dredged material that may contain toxic contaminants are dumped and potentially contaminate groundwater. Artificial structures often replace or are constructed adjacent to some of the richest coastal farmlands and fishery areas. Since the Agricultural Revolution 5000–10,000 BP, coastal waters have been reclaimed for coastal city-state development and trade. Extensive salt marshes of England's Wash were reclaimed as early as 900 AD; only half remain intact today. The Zuiderzee of the Netherlands was closed off from the sea for agriculture, which caused significant loss of estuary-dependent species (Hood, 2004); brackish lakes (polders) emerged behind high dikes that now protect more than half of the Dutch population from rising seas. The short supply of land along Japan's coasts is augmented by artificial islands, which have expanded human occupation, industries, and sea farming.

Physical coastal structures intensely serve the needs of gigantic petrochemical complexes, harbors, steel mills, power plants, urban centers, tourism, recreation, international trade, and shipbuilding facilities as they alter the coastal system (Fig. 2.15). Offshore oil and gas extraction from fixed platforms requires onshore facilities and a variety of shore-stabilizing structures (e.g., seawalls, dikes, etc.), which alter tidal conditions and habitats (Hood, 2004). Artificial structures may enhance dispersal of nonindigenous species by creating a system of "novel" habitats favorable for invasive species in coastal waters (Glasby and Connell, 1999).

2.3.3.2 Obstructed water flow

Man-made dams pervade present-day river systems worldwide (Freeman *et al*., 2003), impeding water flows into coastal systems. In northern Europe, six dams obstruct the Rhine watershed on its route to the North Sea. The Nile, the world's longest river, drains more than 3 million km^2 of watershed of nine countries and once flowed directly into the southeastern Mediterranean Sea. Construction of Egypt's Aswan High Dam and seven other large dams drastically reduced the Nile's flow into the Mediterranean Sea, fundamentally affecting fisheries and coastal ecology. In South America, 29 large dams on the Paraná River affect the 2.5 million km^2 Pantanal wetland that straddles four countries; several more are planned to control floods and generate electric power. Dams built for flood control on Laos' upper Mekong River and its tributaries have destroyed major freshwater fisheries and the spawning and nursery habitats of the river's unique and endangered giant fishes, even before the flow enters the 2200 km-long lower Mekong, which empties into the South China Sea. Laos is planning to construct a dozen more hydropower projects on the lower Mekong, and Cambodia is constructing one more near its mouth (Stone, 2011). The world's largest dam is China's Three Gorges Dam on the Yangtze River, a river in which 45,600 large and small dams intercept its flow path into East China Sea, which supports a major fisheries area.

For centuries, dams have been constructed across rivers to produce energy, mitigate against destructive floods and droughts, and to provide water to farms and cities. The number of large dams increased seven-fold worldwide during the major dam-building period between 1950 and the mid-1980s. These obstructions block migratory fauna, impact fisheries, imperil

Fig. 2.15 Baltimore Harbor in Maryland has been transformed from a natural harbor at the fall line of the Patuxent River into a major port observed here in 1977, hard armored to stabilize its shore for concentrated development that the city supports today. Photograph © Ray & McCormick-Ray.

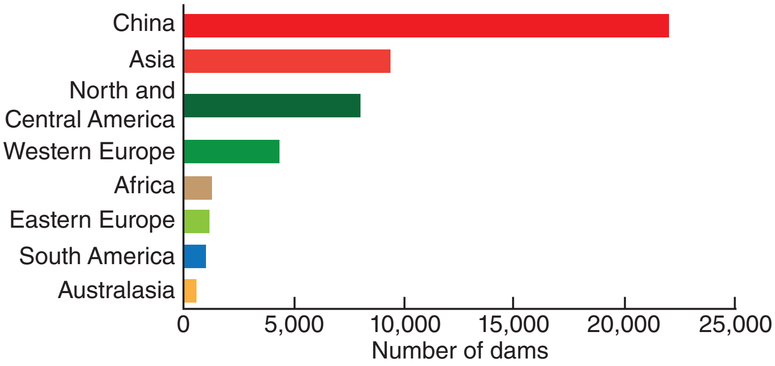

Fig. 2.16 Regional distribution of large dams worldwide in 2000; more than half are in China alone. A large dam is defined as 15 m or higher, or between 10 and 15 m depending on criteria, e.g., reservoir capacities. Today, >45,000 large dams worldwide are spread across 150 countries. From World Commission on Dams (2000). Reproduced with permission of Taylor & Francis.

obligate riverine species, and impede sediment flow important to coastal beaches, shores, and estuaries. An estimated 800,000 large dams existed in 1997, 45,000 of them higher than a five-story building, with more than half built in China (Fig. 2.16). Dams are a primary reason for declines or extirpations of diadromous fish (shad, herrings) in the eastern United States, salmons (*Oncorhynchus* spp.) of the Pacific Northwest, and scores of other fish species elsewhere (Kocovsky *et al*., 2009). Although many stream-dependent species may persist in dam-altered basins, populations restricted to fragments of their former ranges are reduced in abundance (Freeman *et al*., 2003). Also due to dam construction, estuaries at the mouths of three of the world's largest and most famous rivers (Nile, Mississippi, Yangtze) are starved of sediments and their deltas are rapidly disappearing and becoming less productive.

2.3.3.3 Ports and coastal mega-urban centers

Many of the world's largest cities and ports occupy coastal systems (Martínez *et al*., 2007; Table 2.4), especially estuaries and protected regional seas. Rapid growth in international trade and increased vessel traffic has spurred development of ports important to national economies. Ports serve major cities through active loading, unloading, storage, and transport of materials in complex port operations, where fires, explosions, and toxic releases cause serious impacts and chronic degradation (Darbra and Casal, 2004; Table 2.5). U.S. ports are economic development engines that hold remarkable autonomy (Giuliano, 2007). In England's North Sea, vessels that support oil fields cause most accidents (Sii *et al*., 2003). Port developments along the Pacific and Indian Ocean shipping routes are expanding into megacities that degrade waterways. The Pearl River Delta of southern China that includes Hong Kong is rapidly developing industrial, municipal, and agricultural activities over 8000 km^2 of delta, causing serious toxic organic pollution (Fu *et al*., 2003). This Port's annual traffic volume of 40,000 ocean-going ships and 200,000 coastal vessels maneuvers among ferries, barges, and recreational and fishing boats and experienced 2012 accidents between 2001 and 2005 (Yip, 2008).

Ports in developed nations have long been subject to chronic toxic pollution sequestered in sediments, in which fish diseases are reported (Murchelano and Wolke, 1991); e.g., high levels of PCBs are reported in catfish, blue crabs, and speckled trout in the Houston Ship Channel, where about 40% of the U.S.

Table 2.4 World's major ports and megacities occur on major coastal waters. Concrete and steel separate land and sea but unite global trade.

World's largest cities/ ports (country)	Area (km^2)	Population (million)	Traffic port container (TEUs**) (millions)	River system and coastal water	Port max. draft (m)
Singapore* (Singapore)	1200	6.4	29.9	Straits of Malacca	12.5
Shanghai* (China)	6340	24.8	28.0	Yangtze Delta, East China Sea	7.0–12.5
Hong Kong* (China)	1104	7.1	24.5	Pearl R. estuary, South China Sea	Deep
Shenzhen* (China)	72.6	9.6	21.4	Pearl R. estuary, South China Sea	3.0
Busan* (South Korea)	—	3.7	13.4	Korean Straits	16.0
Dubai Ports (U. Arab Emir)	—	1.0	11.8	Persian Gulf	7.2
Ningbo* (China)	2462	2.3	11.2	Yangtze R. Delta, East China Sea	Deep
Guangzhou* (China)	—	25.2	11.0	Pearl R. estuary, South China Sea	3.0
Rotterdam* (Netherlands)	105	2.8	10.8	Rhine R./Meuse R., North Sea	24.0
Qingdao* (China)	—	3.9	10.0	Yellow Sea	17.5
Hamburg* (Germany)	—	2.6	9.7	Elbe R., North Sea	7.0–17.0
Kaohsiung* (Taiwan)	—	2.8	9.7	Taiwan Strait	8.2
Antwerp (Belgium)	204	0.5	8.7	Scheldt Estuary, North Sea	11.5
Tianjin* (China)	107	9.7	8.5	Haihe R., Bohai Bay, Yellow Sea	18.0
Port Kelang (Malaysia)	573	0.6	8.0	Kelang R., Strait of Malacca	13.3
Los Angeles* (USA)	30	18.1	7.9	Pacific Ocean	16.2
Long Beach (USA)			6.4	Pacific Ocean	12.0
Bremen/Bremerhaven (Ger.)	400	0.1	5.5	Geest R., Weser estuary, North Sea	14.5
Tanjung Pelepas (Malaysia)	3.1 M	0.9	5.5	Pulai R. estuary, Strait of Malacca	15.0–19.0
New York/New Jersey Metropolitan area (USA)	3900	18.9	5.3	Hudson estuary, New York Bight	—
Laem Chabang (Thailand)	10	0.006	5.1	Gulf of Thailand	14.0
Xiamen* (China)		2.4	5.0	Jiulong River, Taiwan Straits	14.0
Dalian* (China, PR of)	15	3.6	4.5	Yellow Sea	23.0
Tanjung Priok (Indonesia)	6	—	4.0	Java Sea	3.0–12.0
Nhava Sheva (India)	—	0.2	4.0	Arabian Sea	12.0–13.5
Tokyo* (Japan)	—	34.3	3.7	Tokyo Bay, Pacific Ocean	10.5

*Based on population criteria of world's 26 megacities (>1 million inhabitants), the area of central city and linked neighboring communities. Source: Thomas Brinkhoff online www.citypopulation.de **TEU (or teu) "Twenty-Foot Equivalent Unit" the standard linear measurement used in quantifying container traffic flows.

chemical production and oil refineries is concentrated (Howell *et al.*, 2008). Dredging of ever-deeper channels to accommodate increasingly large cargo and container ships releases toxics to the water column, while increasing ship traffic also pollutes the air. Emerging industrial nations lack the capacity to deal with contaminated sediments.

2.4 TERTIARY ISSUES: EMERGENT AND UNINTENDED CONSEQUENCES

Humans have for centuries, if not millennia, been foremost agents of environmental change. Today, the world's coastal and ocean ecosystems are experiencing unprecedented rates of biological and ecological change from historic and systemic consequences that are most difficult to address. Observations of ocean change draw attention to regional and global issues and a mounting environmental debt from historical abuses that is threatening the natural resiliency and sustainability of many coastal and marine systems as well as local economies. Tertiary issues thus call attention to multiple sources that cumulatively are moving marine ecosystem performance toward undesirable change. We consider only a few of the most notable.

2.4.1 Degraded coastal water quality

On a global scale, nutrient loads from human activities are entering coastal systems to over-enrich (e.g., nutrient pollution) and degrade water quality (Nixon, 1995). Nutrient enrichment increases water turbidity, degrades habitat, alters

Table 2.5 Vessels and port routine operations and episodic-accidental events degrade coastal habitats and sea life through chronic exposures.

EPISODIC events	ROUTINE operations
Vessel impacts	
Collisions with sea life	Underwater noise
Vessel collisions	Air emissions
Toxic and cargo spills	Ballast water release/hull fouling of exotic species
Sewage release	Hull coating toxic release
Ocean dumping	Lights
Oily waste water	
Port impacts	
Dredging maintenance, toxin releases	Storm water runoff—sediment, toxins
Port expansion/land reclamation	Vessel wake erosion
Ship construction	Cargo-handling air emissions
Explosions/accidental spillage	Habitat alteration (estuary, sea grass)
Ground transport collisions/spillage	Shoreline stabilization/alteration
	Lights: timing; intensity
	Altered currents/hydrodynamics
	Artificial habitats encourage exotic species
	Dust generation
	Noise

food-web structure, reduces biodiversity, and initiates harmful algal blooms (Howarth, 2008). These effects can alter marine food webs critical to commercial fisheries and lead to ecological changes detrimental to estuaries, coral reefs, and other habitats important to marine biodiversity and ocean productivity.

Human activities linked to coastal degradation concentrate mostly in bay and estuarine habitats (Vitousek *et al.*, 2009), with consequences for human health (Emch *et al.*, 2008; de Magny *et al.*, 2010). Ill health affects species inhabiting overdeveloped and simplified environmental systems, where high stress conditions may compromise their immunity to microbial infection (Harvell *et al.*, 1999). High daily loads of wastewater that empty into coastal waters add bacteria, viruses, and numerous other forms of human pathogens into marine reservoirs. Evidence indicates that marine organisms host a diversity of parasites and pathogens (Stewart *et al.*, 2008), some of which are pathogenic to a variety of sea life (Munn, 2006). Viruses are abundant and play enormous roles in ocean processes (Ch. 5), and bacteria from sewage effluents are contributing to antibiotic-resistant bacterial lesions in fishes (Al-Bahry *et al.*, 2009) and to coral diseases (Sutherland *et al.*, 2011). Also, "sick seas" may be sickening marine mammals (Lowenstine, 2004), alarming the general public (Noga, 2000).

2.4.1.1 Expanding anoxic bottom waters

Over-enrichment leads to eutrophication and low oxygen concentration (hypoxia), lack of oxygen (anoxia), and to "dead zones" (Box 2.5) in which all organisms that require dissolved

Box 2.5 Hypoxia

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Rutger Rosenberg
University of Gothenburg, Sweden

Low dissolved oxygen environments (known as hypoxic or dead zones) occur in a wide range of aquatic systems and vary in frequency, seasonality, and persistence. While there have always been naturally occurring hypoxic habitats, anthropogenic activities related primarily to organic and nutrient enrichment related to sewage/industrial discharges and runoff from agricultural lands have led to increases in hypoxia and anoxia in both freshwater and marine systems. A consequence of this over-enrichment has been a rapid rise in the areas affected by hypoxia over the last 50 years. No other environmental variable of such ecological importance to estuarine and coastal marine ecosystems as dissolved oxygen has changed so drastically, in such a short time. Currently there are over 500 hypoxic areas or dead zones around the world related to human activities (Fig. B2.5.1).

By the early 1900s dissolved oxygen (DO) was a topic of interest in research and management, and by the 1920s it was recognized that a lack of DO was a major hazard to fishes. It was not obvious, however, that DO would become critical in estuarine and shallow coastal systems until the 1970s and 1980s when large areas of low dissolved oxygen started to appear with associated mass mortalities of invertebrate and fishes. From the middle of the 20th century to today, there have been drastic changes in dissolved oxygen concentrations and dynamics in many marine coastal waters. Prime examples would be the northwest continental shelf of the Black Sea, the Baltic Sea, the Gulf of Mexico continental shelf off Louisiana and Texas, and the East China Sea.

There is a similarity of faunal response across systems to varying types of hypoxia that range from beneficial to mortality. Consequences of low DO are often sublethal and can affect growth, immune responses, and reproduction. When a system becomes hypoxic, mobile fauna have to contend with two simultaneous problems: (i) loss of habitat as they are forced to migrate into higher DO waters; and (ii) increased risk of negative species interactions and

(*Continued*)

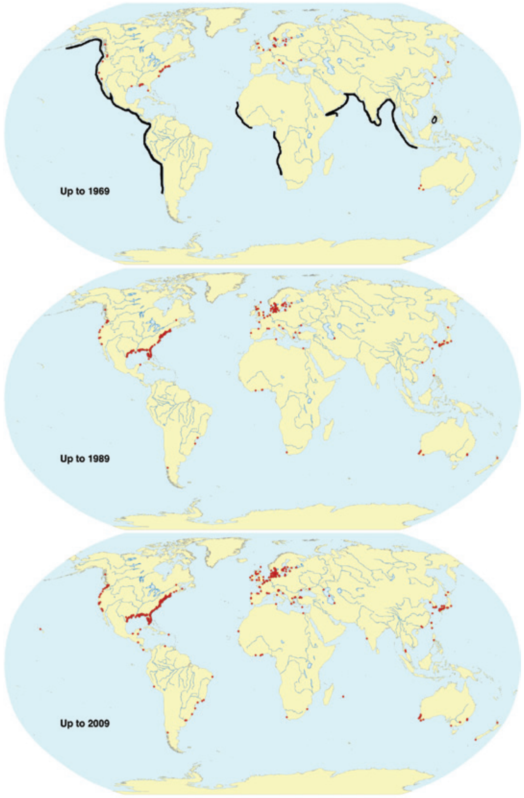

Fig. B2.5.1

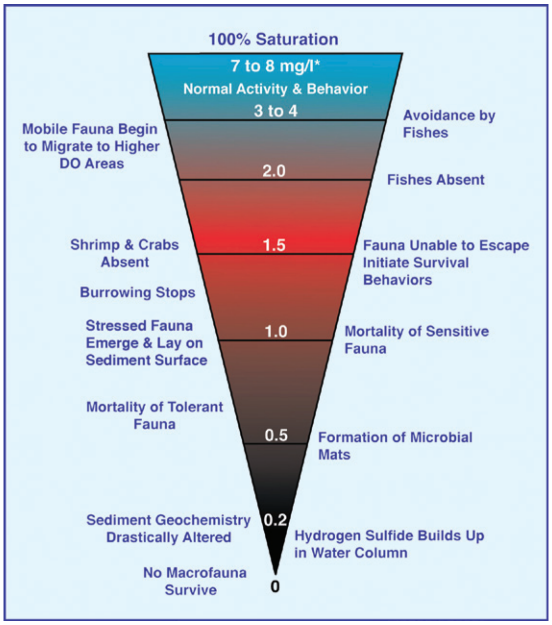

Fig. B2.5.2

predation. Sessile fauna initiate a graded series of behaviors to survive and will eventually die as DO declines or extends through time (Fig. B2.5.2).

Climate change, whether from global warming or from microclimate variation, will have consequences for eutrophication-related oxygen depletion. Climate change may make systems more susceptible to development of hypoxia through direct effects on water column stratification, solubility of oxygen, metabolism, and mineralization rates. This will likely occur primarily through warming, which will lead to increased water temperatures and a subsequent decrease in oxygen solubility, and an increase in organism metabolism and remineralization rates. Indirect effects on the quality and quantity of organic matter produced will also be important. All factors related to climate change will progressively lead to an onset of hypoxia earlier in the season and possibly extending it through time. Earlier warmer surface waters would also extend and enhance water column stratification intensity.

Much of how climate change will affect hypoxia in estuarine and coastal systems will depend on coupled land-sea interactions with climate drivers. The future pervasiveness of hypoxia will also be linked to land management practices, expansion of agriculture to feed a growing global population, and production of biofuels. Climate change will affect physical and biological processes of water column stratification, organic matter production, nutrient discharges, and rates of oxygen consumption. Land management will affect the nutrient budgets and concentrations of nutrients applied to land through agriculture. If in the next 50 years humans continue to modify and degrade coastal systems as in previous years, human population pressure will likely continue to be the main driving factor in the persistence and spreading of coastal dead zones. The expansion of agriculture for production of crops to be used for food and biofuels will result in increased nutrient loading, expand eutrophication effects, and contribute to greenhouse gases. Overall, climate drivers will tend to magnify the effects of an expanding human population.

Climate-related changes in wind patterns are of great concern for coastal systems as they control Ekman transport and upwelling/downwelling strength, which would affect stratification strength and delivery of deep-water nutrients into shallow coastal areas. Even relatively small changes in wind and current circulations could lead to large changes in the area of coastal seabed exposed to hypoxia, particularly along the Pacific coast. Changes in the pattern of upwelling in Pacific coastal waters off the Oregon and Washington coasts, due to shifts in winds that affected California current systems, appeared to be responsible for the recent development of severe hypoxia over a large area of the inner continental shelf.

oxygen are depleted or perish, thus leading to deterioration of the structure and function of the ecosystem. Marine hypoxia/anoxia is a source of greenhouse gases, methane (CH_4), and nitrous oxide (N_2O) (Naqvi *et al.*, 2010). Benthic hypoxic/anoxic areas have spread exponentially since the 1960s, with few reverses (Diaz and Rosenberg, 2008). A dead zone was first observed in the northern Gulf of Mexico in the mid-1970s (Rabalais *et al.*, 2002), which is maintained year-round by the eutrophic Mississippi and Atchafalaya rivers, pouring nutrients into the system (Turner *et al.*, 2008). This hypoxic zone reached an average size of 13,600 km^2 between 1985–2010 that increased to as much as 26,515 km^2 in 2011 (Rabalais and Turner, 2011), surpassing the 12,000 km^2 hypoxic/anoxic waters of the East China Sea (Chen *et al.*, 2007).

2.4.1.2 Regional change

Rapidly deteriorating coastal seas are losing biodiversity. The semi-enclosed Mediterranean Sea, dominated by coastal developments that house about 150 million people and 200 million tourists seasonally, exhibits poor health (El-Sayed, 2008) and loss of biodiversity (Bianchi and Morri, 2000). Overfishing has removed indigenous fishes (Tudela, 2004), and the opening of the Suez Canal in 1869 connected two biogeographical provinces (Atlanto-Mediterranean and Indo-Pacific) and introduced more than 300 Red Sea species into the Mediterranean's eastern portion (Spanier and Galil, 1991). Red Sea jellyfish (*Rhopilema nomadica*) now proliferate along the Levantine coast, profoundly affecting indigenous biota and causing significant ecologic and economic consequences (Galil, 2000). Introductions of non-native toxic fishes are now public health concerns for ciguatera and tetrodotoxin (Bentur *et al.*, 2008).

In the U.S., air, sediments, and organisms in the urban, intensely developed San Francisco Bay are polluted. High mercury concentrations are found in fish-consuming birds (Ackerman *et al.*, 2008). Concentrations of the unregulated and widely used flame retardant, polybrominated diphenyl ethers, which dramatically increased during the last decade, occur in humans; levels in harbor seals (*Phoca vitulina richardsi*) are amongst the highest known (She *et al.*, 2002). The more than 210 invasive species, including the proliferating European green crab (*Carcinus maenas*) and cordgrass (*Spartina* sp.), are reducing native populations, impacting ecological transfers, and altering ecosystem function (Grosholz and Ruiz, 2009). And wetland habitat has been destroyed by reduction of freshwater inflows from diking and filling (Nichols *et al.*, 1986). Total impacts are decreasing estuarine-dependent fish in the Bay (Feyrer *et al.*, 2007).

The northern Gulf of Mexico is another region, among many, exhibiting change. A spectacular number of jellies (*Phyllorhiza punctata*) erupted in summer 2000. The Gulf received the disastrous *Deep Horizon* Gulf oil spill in 2010, as well as increased nutrient-enriched runoff from the Mississippi River (Milly and Dunne, 2001), powerful hurricanes (e.g., Ivan, Katrina, Rita), and devastating 27 m-high waves (Stone *et al.*, 2005) that severely impacted its coasts, wetlands, and numerous oil and gas platforms (Turner, 1997). In 2002, the Gulf of Mexico and the East China Sea had the largest dead bottom areas in the world (Rabalais *et al.*, 2002).

The East China Sea, the Yellow Sea, and Bohai Sea in Southeast Asia are undergoing major modification, exhibiting eutrophy, hypoxia, and fishery collapses due to overfishing. The North Sea, Wadden Sea, and Baltic Sea are among others exhibiting major impacts. Growth in industrial fishing, human populations, industrialization, agro-industries, and water use make clear that as much as 41% of the world's coastal-marine ecosystems are "strongly affected by multiple drivers" (Halpern *et al.*, 2008).

In sum, no regional sea is unaffected by human influences, with most being strongly affected by multiple drivers. Overfishing and nutrient enrichment are two synchronous anthropogenic effects increasingly impacting semi-enclosed seas since World War II (Caddy, 1993, 2000). Within these ecosystems, synergistic effects interfere with wildlife, feeding hierarchies, setting off an initial increase in productivity of benthic/demersal and pelagic food webs due to "bottom-up" and "top-down" impacts. These impacts lead toward a progressive predominance of short-lived pelagic species (nuisance species). Biomass removal from the most productive ocean ecosystems (upwelling areas, temperate continental-shelf systems, etc.) removes primary production from that system (Pauly and Christensen, 1995), changes energy flow and species dominance, and causes profound, poorly explored impacts that are raising concern. The removal of fishes from Large Marine Ecosystems (LMEs, Ch. 4), areas that produce the major portion of global fisheries yield, affects ecosystem structure, function, and fish yields (Worm *et al.*, 2006). Removing apex predators from pelagic food webs, i.e., removing the largest and oldest individuals, causes an ecological cascade that can restructure food webs (Myers and Worm, 2003; Kitchell *et al.*, 2006). The excessive removal of cod, for example, has disrupted food-web energy flow, which caused a progressive decline of the benthic system (Frank *et al.*, 2005). Removal of large sharks has resulted in increased nuisance prey species, for example over-abundance of cownose rays that feed on scallop beds, thereby forcing closure of a century-long scallop fishery (Myers *et al.*, 2007). Evidence makes clear that historical overfishing of large marine vertebrates, i.e., whales, sea turtles, manatees, seals, fishes, and others, has affected the functional performance of ecosystems. For example, overfishing productive coastal seas that have complex food webs, high biomass, and large animals may simplify biological systems, amplifying boom-and-bust fishing cycles. As these systems become increasingly disturbed and overfished, energy that goes into fisheries production increasingly favors microorganisms and jellies (Jackson *et al.*, 2001; Mills, 2001). Some LMEs appear to have increasing abundance of jellies (Brotz *et al.*, 2012), but their global rise is difficult to substantiate (Condon *et al.*, 2012), being masked by normal fluctuations (Arai, 2001) and exacerbated by climate change (Gibbons and Richardson, 2009). Jelly increases may be due to combinations of overfishing, eutrophy, introduced species, and habitat modification that restructure pelagic ecosystems into less desirable states (Richardson *et al.*, 2009). The overall impact reduces biodiversity, species recovery potential, ecosystem stability, and water quality (Worm *et al.*, 2006).

2.4.2 Global ocean change

Changes occurring in the global ocean relate to climate, global cycles, and the stability of the Earth's cybernetic processes.

2.4.2.1 Climate and ocean warming

Warming of the climate system is unequivocal (IPCC, 2007; Hansen *et al*., 2012), and change can be abrupt (NRC, 2002b). Global climate temperature increased considerably during the 20th century, especially since the 1970s (Jones and Moberg, 2003; Vose *et al*., 2005; Gleason *et al*., 2008), although the timing and severity of warming, its regional impacts, and the magnitude of feedback processes remain uncertain (Millero, 2007). However, subpolar ice and mountain glaciers are declining in mass worldwide (Dyurgerov, 2003; Oerlemans, 2005; Ch. 7). The world ocean is a significant temperature sink with a close connection to climate (Ch. 4).

The world ocean is warming, with robust certainty (Levitus *et al*., 2005, 2009; Lyman *et al*., 2010; Fig. 2.17a). Its upper 700 m has warmed an average of 0.18°C over the last 40 years (IPCC, 2007) and is predicted to increase within decades. There may be significant warming below 700 m depths as well (Trenberth and Fasullo, 2010). Rates of change are fastest in the Arctic Ocean and adjacent seas (Spielhagen *et al*., 2010), threatening the survival of ice-dependent species (Ch. 7); loss of sea ice set summer records in 2007 (Perovich *et al*., 2008), which was exceeded in 2012 (National Snow and Ice Data Center, online). Sea-ice loss is helping to open an area rich in oil and gas and cruise boat opportunities. This loss is also bringing promise of new, shorter shipping routes and initiating a race among Arctic nations to claim jurisdiction over extensive natural resources on continental shelves (Ch. 3). Polar sea-ice melt and diminishing ice caps on Greenland and Antarctica are most striking examples of global climate change.

2.4.2.2 Sea-level rise

A model analysis indicates a close link between global temperature and the rate of sea-level rise (Vermeer and Rahmstorf, 2009). Melting of Greenland and Arctic continental ice sheets and the expansion of seawater volume from ocean warming contribute to global sea-level rise. Throughout the 20th century, global sea level has risen at an accelerating rate

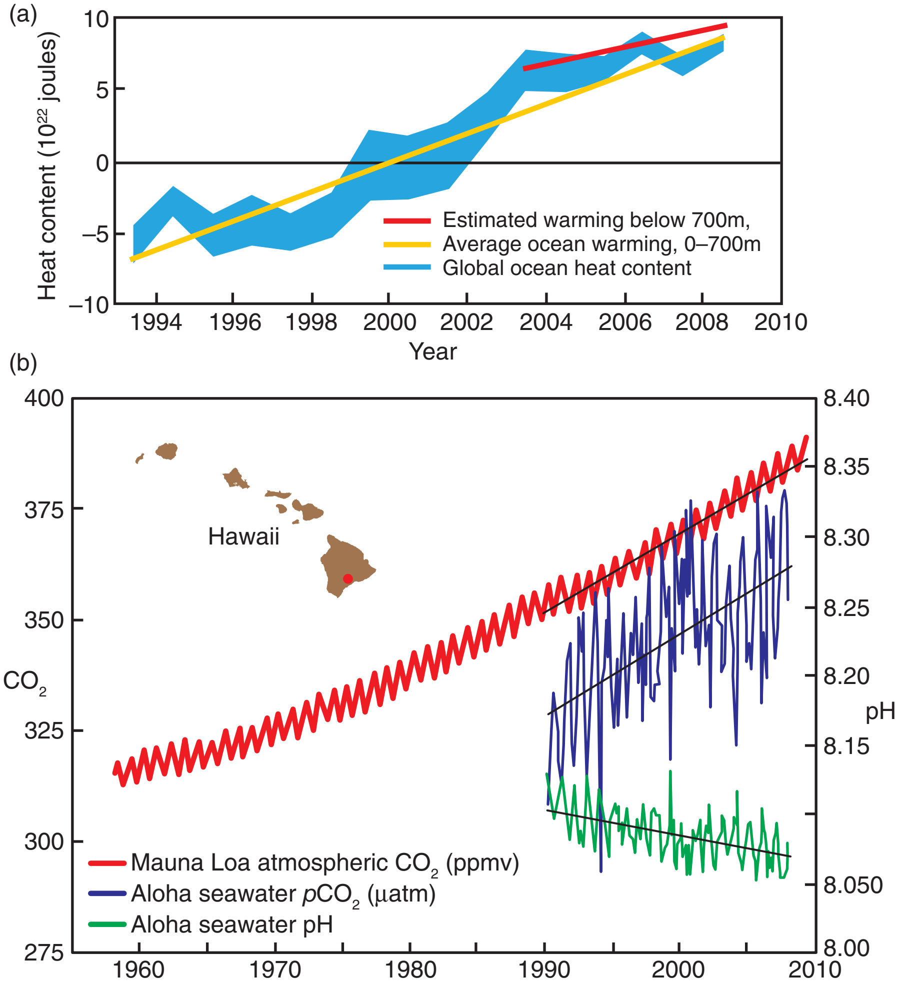

Fig. 2.17 Trends in ocean warming, carbon dioxide (CO_2) concentrations, and ocean acidification. (a) Increasing global ocean heat content encompassing error range with respect to mean (blue), showing an average (0.64 watts m^{-2}) increase from surface to 700 m depths (yellow); estimates below 700 m also show increases (red). Trenberth 2010. Reprinted with permission of MacMillan Publishers Ltd. (b) Increasing trend in atmospheric CO_2 concentrations (red), surface ocean carbon dioxide (pCO_2, purple), and decreasing ocean surface acidity (pH, green) measured at Mauna Loa, Hawaii. From Doney SC, Balch WM, Fabry VJ, Feely RA (2009) *Oceanography* **22**, 16–25, with permission.

(Church and White, 2006), and since 1950 it has risen by an average of 1.7 ± 0.3 mm year^{-1} (Domingues *et al.*, 2008). Rising sea levels and the potential for stronger storms threaten the world's coastal regions, flooding many of the largest and most densely populated cities, ports, and low-lying regions and islands, e.g., Hurricane Sandy that devastated the northeastern U.S. in October 2012. Low-lying Bangladesh and island nations such as Kiribati, the Maldives, and The Bahamas are further subjected to increases in hurricanes, typhoons, and tsunamis resulting from climate change.

2.4.2.3 Altered water cycle

Growing human demands for water and groundwater sources (Konikow and Kendy, 2005) are depleting and polluting/degrading water ecosystems (Rosegrant *et al.*, 2002), worsened by climate change (Vörösmarty *et al.*, 2000), and impacting the terrestrial water cycle on a global scale (Hoff, 2002). Humans withdraw about 10% of the globally available freshwater from rivers and groundwater each year (Oki and Kanae, 2006), with 50% from groundwater for drinking (Llamas and Martínez-Santos, 2005) and increasingly for irrigation and non-consumptive uses, both of which have increased in the last 50 years. Large-scale changes in freshwater flux have potentially important implications for ocean circulation, climate (Peterson *et al.*, 2002), and the hydrologic cycle (Rahmstorf, 1995). Terrestrial water storage associated with dam building (Section 2.3.3.2; Chao *et al.*, 2008) and groundwater mining contributes to changes in global water cycling, through processes yet to be understood (Domingues *et al.*, 2008). Climate change and groundwater depletions together are globally affecting the global hydrologic cycle and decreasing water quality and yields, which damage ecosystems, cause land subsidence, and increase pumping costs. Higher temperatures will increase the snowmelt season, turn snowfall into rainfall, and substantially change the timing and volume of spring flood, altering hydrologic conditions important to coastal ecosystems, especially estuaries.

2.4.2.4 Altered biogeochemical cycling: sinks, sources, and transformation

The oceans play a critical role in global biogeochemical cycles (Schlesinger, 1997; Sarmiento and Gruber, 2006) that human activities are significantly influencing (Galloway *et al.*, 2004; Duce *et al.*, 2008; Doney, 2010). The role of oceans directs attention to key biogenic elements of carbon and nitrogen (Jickells, 1998) and to heat-trapping gases ("greenhouses gases": carbon dioxide, CO_2; methane, CH_4; nitrous oxide, N_2O; fluorinated gases, etc.). Heavily populated coastlines release reactive nitrogen, which increased nearly 80% between 1860 and 1990 (JOCI, 2008) to fertilize and degrade coastal water, China's releases being globally significant (Zhang, 2002). And marine vessels are contributing a large portion of the world's greenhouse gases; international shipping in 2007 contributed an estimated 2.7% to global CO_2 emissions (Buhaug *et al.*, 2009). These releases are expected to increase as ships become larger and more numerous.

The rise in CO_2 concentrations influences the global carbon cycle and increases ocean acidification (Feely *et al.*, 2004). Oceans have absorbed an estimated third of the CO_2 released by human activities between 1800 and 1994 (Sabine *et al.*, 2004). And along with increases in carbon dioxide emissions, the powerful and persistent nitrous oxide gas (N_2O) is on the rise, with methane gas also playing an increasingly important role (Heimann, 2010). These greenhouse gases, with water vapor and chlorofluorocarbons (CFCs), are increasing in the atmosphere and increasing global temperatures (Millero, 2007; Doney, 2010); their interplay with the ocean is an active field of research.

2.4.2.5 Ocean acidification

The input of gigatons of carbon dioxide into the oceans is acidifying ocean water, i.e., lowers its pH, where pH is a measure of acidity (Fig. 2.17b; NRC, 2010b). Ocean acidification results when carbon dioxide combines with water to instantly form bicarbonate (HCO_3^-) and hydrogen ions—the H+ that increases acidity that causes major impacts on marine organisms (Feely *et al.*, 2004). The impact of ocean acidity on sea life is varied. Evidence reveals that in sufficient concentration it can lower net calcification (Ries *et al.*, 2009). Ocean acidity impairs such animals as clams, oysters, corals, and more, interfering with their capacity to extract calcium carbonate to build their skeletons or shells. When hydrogen ion concentrations are high enough and carbonate concentrations are driven down, an organism's calcium carbonate shell begins to dissolve, which increases the energetics required by organisms to extract carbonate from surrounding water. Early signs of ocean acidification and its effects on organisms (Orr *et al.*, 2005; Yamamoto-Kawai *et al.*, 2009), are affecting calcium-carbonate shells and skeletons for a broad range of marine species, e.g., corals, microscopic protozoa, certain algae (Guinotte and Fabry, 2008). This effect is supported in a controlled study carried out at Woods Hole Oceanographic Institution (WHOI, 2010; Fig. 2.18; Ries *et al.*, 2009).

The regions with greater capacity for carbon dioxide absorption are cold, high-latitude surface waters. They are first to experience the impact, then the tropics (Feely *et al.*, 2004). This effect is, however, far from clear due to regional differences and the diversity of tolerances among species and their complex life histories. How these impacts translate into ecosystem change is unknown, but one thing is certain: acidification is massive and rapid and the more carbon dioxide emitted, the worse it is going to get—"an experiment we would not choose to do" (Kerr, 2010). Quick and aggressive emissions reductions are key to minimizing this apparently irreversible acidification process.

2.5 THE CHALLENGE FOR THE 21ST CENTURY

Primary issues awaken us to diminishing biological richness, loss of ocean habitat, proliferation of undesirable nuisance and harmful species, ill health, and effects on critical ecosystems (Millennium Ecosystem Assessment, 2005). Secondary

Fig. 2.18 Impact of ocean acidity on sea life, as studied by Justin Ries at Woods Hole, Massachusetts. Right: sea urchin grown under present-day ocean acidity has normal spines and appears healthy. Left: sea urchin grown under higher CO2 concentrations in more acidic seawater conditions is substantially damaged. Photograph by Tom Kleindinst © Woods Hole Oceanographic Institution.

issues highlight the concentration of human activities in the coastal fringe—removing resources, adding foreign substances, and physically altering coastal systems through human activities that are expanding in magnitude, duration, and intensity. Tertiary issues draw attention to emergent phenomena, with global losses of ecological services that are moving Planet Earth beyond a safe operating space for humanity—its planetary boundaries (Rockström *et al.*, 2009), including climate change, biodiversity loss, and human interference in the nitrogen cycle, whose boundaries have already been exceeded.

Increasing world population and resource demands challenge individuals and society to confront ecosystem limits through decision-making power to protect, restore, and conservatively use the benefits and services that coastal and marine ecosystems provide. The dynamic interactions between land, sea, air, and human influences are moving local, regional, and global ecosystems into an unpredictable future burdened with environmental debts from historical abuses. Marine conservation is equipped with an arsenal of advancing and evolving social mechanisms (Ch. 3) and increasing scientific understanding (Chs. 4, 5) needed to address the accelerating pace of this intensifying *Anthropocene* era (Steffen *et al.*, 2007; Ch. 13). The range of issues presented here are global in scope, demanding a multi-scale, global system focus.

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