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Temperate Coastal Marine Communities: Biodiversity and Threats[1]

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SYNOPSIS. Temperate marine ecosystems are some of the most productive and diverse of all ecosystems. Over the past century the resources contained within these communities have been subjected to gross mismanagement. They are continually subjected to threats from multiple stresses imposed mostly by human activities, predominantly as a result of increased population growth. The most significant categories of threats derive from: (1) habitat loss and degradation, (2) pollution from numerous sources including sewage, pesticides, pulp mills, thermal effluents, polychlorinated biphenyls, heavy metals, oil and radionuclides, (3) overexploitation, (4) species introductions, (5) global climate change, (6) misguided human perceptions and (7) legal complexities. Furthermore, because subtidal and offshore coastal marine communities are not easily observed, their deterioration often goes mostly unnoticed.

Impacts from stresses on coastal marine communities are manifested at the individual species level, but magnify in effect throughout the entire ecosystem because of complex inter-connected relationships between species at different trophic levels, including interactions such as predation, competition and mutualism. Therefore, one missing species or group of species that may be affected by some particular local pollutant, for example, may have unpredictable direct or indirect consequences through secondary effects on the ecosystem, possibly leading to the loss of a few to many species. Rather than striving to maintain some specific level of diversity, we should endeavor to understand the basic ecological processes that control populations, communities and ecosystems so we can best predict what kinds of stresses will cause the most serious alterations to the system and avoid them. In addition, we should be conservative about protecting systems even before we understand the processes fully.

INTRODUCTION

In 1609 Hugo Grotius published his treatise "MARE LIBERUM," in which he stated that (1) the seas should be free "for the innocent use and mutual benefit of all" and (2) the seas could not be spoiled and therefore did not need protection (Fye, 1982). This set the stage for continued overexploitation and degradation of the oceans in general and coastal resources in particular, without responsibility for stewardship. Hence began the oceanic version of Garrett Hardin's "Tragedy of the Commons." Under this philosophy, resources available as a common resource pool are exploitable by everyone, but are the responsibility of none. This has been the cornerstone of the most significant threats to coastal marine communities, especially over the past 150 years. MARE LIBERUM was not significantly challenged until 1945 when President Truman, by proclamation, unilaterally claimed the natural resources of the seabed of the continental shelf for the United States, although the waters above the seabed were still considered the high-seas. Today we face myriad conflicts over coastal ocean resource

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use. Economic and political forces create ongoing compromise solutions to an expanding population intent on exploiting ever diminishing resources. Herein lie the difficulties and challenges we face in our attempts to protect coastal marine biodiversity.

Over the past two centuries we have witnessed unparalleled negligence, mismanagement and continued degradation of coastal marine habitats in both tropical and temperate zones. It is clear that the vast majority of threats (short-term/long-term, local/global) to coastal marine communities are due to expanding human populations and associated depletion and/or destruction of coastal resources. In the U.S., nearly 50% of the population lives in coastal regions which comprise only about 5% of the total land area (Salm and Clark, 1984; N.O.A.A., 1990). Much of this area is represented by coastal wetlands and estuaries, but in the U.S. these are declining at a rate of about 80 km^2 per year (N.O.A.A., 1990). The population of the 18 nations bordering the Mediterranean is about 376 million (about 70% of those live along the coast), which is expected to swell to 435 million by the year 2000 (Julian and Ryan, 1990). The major concern with this ongoing loss and degradation is that the cumulative effects of multiple stresses to these ecosystems will ultimately cause a collapse of coastal ecosystems. There are numerous historical studies and theoretical paradigms that all point to the same inevitable endpoint if we continue our current practices with respect to coastal ocean management. Here I attempt to document the major complexities of temperate coastal marine ecosystems and relate these to present day threats to coastal marine biodiversity.

Temperate coastal marine communities hold some of the most productive and diverse assemblages of organisms on earth. Kelp beds and estuaries both provide habitats for myriad sport and commercial species, vertebrate and invertebrate. And, exposed rocky coasts support some of the most productive and diverse assemblages recorded on earth, some rivaling tropical marine or terrestrial systems for productivity and diversity. For example, Leigh *et al.* (1987) describe a temperate algal community (the sea palm *Postelsia palmaeformis*) from an exposed habitat in Washington state that has an estimated annual primary productivity of 3.8–14.6 kg/m^2/yr, compared with temperate evergreen and tropical rainforests that range from 1.2–2.7 kg/m^2/yr (also see Whittaker [1975] for other estimates of tropical productivity). And, along the west coast of North America, Suchanek (1992) documents extreme biodiversity (over 300 species) of associated invertebrates found in the interstices of *Mytilus californianus* mussel beds, the result of increased habitat heterogeneity provided by the structurally complex mussels that dominate these rocky shores.

THREATS

The subject of threats to coastal marine resources is so vast that one could not do justice to the topic within a single review paper. Rather, I attempt to outline the major categories of threats and to summarize their potential consequences, yet provide key published resources for those interested in pursuing individual topics further.

1. Habitat loss and degradation

Development of coastal zones results in considerable habitat loss and degradation. Continued coastal urbanization, demand for waterfront residential property and logging result not only in increased sedimentation from run-off over newly excavated soil, but lead to increased human exploitation, trampling and in some cases vehicular traffic over adjacent intertidal areas, with dramatic consequences to mobile and sessile fauna and flora (Beauchamp and Gowing, 1982; Ghazanshahi *et al.*, 1983; Duran and Castilla, 1989; Kingsford *et al.*, 1991; Povey and Keough, 1991).

Coastal wetlands are some of the most productive and important components of nearshore ecosystems and yet they are suffering some of the most serious habitat loss rates. Over 75% of Southern California wetlands have already been destroyed (Zedler, 1991). They are especially important because they provide macroinvertebrates, fishes and birds with unique resources in the form of food and shelter (Simenstad, 1987). They function as nursery grounds for many species that spend their juvenile life in these protected habitats, but which then migrate out to other habitats as adults. In many cases even though habitats are not lost or destroyed, significant degradation of environmental quality may reduce their functional importance to a coastal ecosystem.

2. Pollution

It is hard to know where to start when discussing pollutants entering coastal communities. However, we can categorize coastal pollutants into two major groups: point source waste disposal and non-point source pollutants. Examples of point source pollutants are: *garbage, dredge spoils, sewage/nutrients, chlorinated hydrocarbons* (pesticides), *pulp mill effluents, thermal effluents, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), radionuclides, heavy metals* (including copper, mercury, silver, lead, cadmium and organo-tins), and *oil.* Examples of non-point source contaminants are: *garbage, pesticides, PAHs, radionuclides, heavy metals* and *oil.* Because of effective three dimensional mixing in the coastal environment, these two lists often have common representatives. Some, such as the heavy metals, pesticides, PCBs and radionuclides, bioaccumulate in higher trophic levels, sometimes affecting the physiological functioning of individuals, or causing other ecological or human health problems. Especially relevant to the issue of combined pollution threats in nearshore environments are "sea surface microlayers" that have recently been found to concentrate pollutants at the sea surface, which can affect plankton concentrated at the surface or be deposited on intertidal shores, producing developmental, reproductive and mutagenic effects (Hardy *et al.*, 1990; Hardy, 1991; Gardiner and Hardy, 1992). Below, I provide examples of selected sources of pollution that likely provide some of the greatest threats to biodiversity along our temperate coasts.

Pesticides, PCBs.—It is becoming increasingly evident, and especially over the past four decades, that our coastal environment has been subjected to incredible levels of waste dumping and it is now clear that those compounds are making their way through the food webs. For example, in the relatively pristine appearing Gulf of the Farallons (California) there are subtidal garbage dump sites, dredge spoil dump sites, munitions dump sites, chemical dump sites and nuclear waste dump sites. Fishes taken from this region show liver levels of PCBs and DDTs up to 60 times higher than those from visually more polluted regions of Southern California (Melzian *et al.*, 1987). Sources of contamination at the Farallons sites are believed to include chemical waste dumps, industrial and municipal outfalls, aerial fallout and surface run-off.

Until 1970 roughly 113 kg/day of manufacturing wastes from the production of DDT were being dumped into sewer and industrial waste flumes that ended up in the coastal marine environment of Southern California. Although DDT was banned from use in 1972, it had already bioaccumulated in the coastal ecosystem, causing egg shell thinning in many bird species, embryo malformations in gulls and complete breeding failure of pelicans and cormorants in the late 1960s (Peakall, 1970, 1975). Today eagles (top predators) still exhibit complete reproductive failure in this region. And, DDT is still being used in other countries.

Heavy metals.—One of the early documentations that heavy metals could bioaccumulate to higher trophic levels and produce effects that were ecosystem-wide came from mercury contamination in Minamata Bay, Japan during the 1950s (Eisler, 1987). From 1932–1968 mercury (260–600 tons) was discharged into the bay from an acetaldehyde plant using inorganic mercury as a catalyst. Abnormally elevated mercury levels were found in sediments, invertebrates, fishes, birds and ultimately humans, a result of bioaccumulation. Fishes, terrestrial mammals, birds, humans (and likely many undocumented invertebrates) experienced dramatic neurological disorders and many died. In this case the discharged inorganic mercury itself was not the active agent, but was converted into toxic organic methylmercury by bacteria. Nearly all mercury in higher trophic levels is in the form of methylmercury (Eisler, 1987).

The literature is replete with examples of many other heavy metal elements entering coastal environments as a result of human-based activities. Some examples of the common heavy metals causing problems in the coastal marine environment are: lead from batteries, copper and organo-tins (such as TBT) used in boat bottom paints, cadmium (an element with no known biological function but resembling nutrients in its ability to be assimilated and bioaccumulated), selenium, and mercury (Furness and Rainbow, 1990).

Pulp mill effluents.—Bleached kraft pulp mills are common along shorelines of the Pacific Northwest and Northern California. Chemically complex effluents from these mills have been shown to contain simple inorganic salts and at least 250 organic and inorganic compounds of low molecular weight (Suntio *et al.*, 1988) plus many with high molecular weights. Some fractions of these effluents (typically the high molecular mass compounds) have shown a variety of toxic effects from acute toxicity to sublethal effects on many nearshore marine species, including: phytoplankton, sea urchins, mussels, English sole, salmon and topsmelt (Stockner and Costella, 1976; Kinae *et al.*, 1981; Kringstad and Lindstrom, 1984; Cherr, 1987; Shenker and Cherr, 1990; Owens, 1991; Higashi *et al.*, 1992). Data collected to date indicate that different chemical fractions of these effluents typically yield varying degrees of toxicities for different taxa, so it is difficult to predict specific impacts of the effluent on individual species and even more difficult to predict effects at the community level.

Oil.—Natural oil seeps on the ocean floor introduce petroleum products into the coastal ocean on a regular basis, especially in regions such as Southern California, but those natural sources account for only *ca.* 8% of the total oil that enters the marine environment each year (Suchanek, 1993). The remainder is derived from man's activities including: intentional tank purging, tanker spills, and municipal and industrial sources including coastal refineries. Oil globs often drift to shore, but are partially oxidized and then consumed by marine oleophyllic bacteria. However, when the local environment is deluged with oil from a massive spill, bacteria cannot consume it fast enough and detrimental impacts result. Crude oil in the coastal environment typically breaks up into three major components: a volatile component, a floating component and a sinking component. The volatile component can be 20–50% by volume, depending on the type of oil. This fraction quickly (days to weeks) evaporates into the atmosphere or dissolves into the water column, mostly affecting tiny organisms with a large surface area to volume ratio such as permanent plankton (holoplankton) or temporary plankters including dispersing larvae of invertebrates or fish (meroplankton). The floating component is the fraction that typically gets the most publicity because it affects popular birds (*e.g.*, murres, grebes, eagles) and mammals (*e.g.*, sea otters, seals). Wave action whips this fraction into an aerated slurry called "mousse," often increasing the original volume several fold. It reduces the insulative and flotation functions of fur and feathers for vertebrates and suffocates shoreline invertebrates. Because of the floating nature of this fraction, intertidal communities are especially vulnerable. Studies of past spills in temperate coastal habitats indicate that mousse is mostly indiscriminate with respect to impacts on various taxonomic groups; if covered heavily by mousse, most species are killed. When it occurs (depending on the relative density of the oil and potential mixing with sediments), the sinking component can impact subtidal communities as well.

Some of the best data on recovery of oil impacted temperate coastal communities derive from the 1969 West Falmouth diesel fuel spill in Massachusetts (for protected soft sediment habitats), and the 1978 Amoco Cadiz crude oil spill off the coast of Brittany, France and the 1989 Exxon Valdez crude oil spill in Alaska (for rocky shores). In 1989, some 20 years after the West Falmouth spill, oil traceable to the 1969 spill was still found buried in both marsh sediments from the most heavily impacted areas as well as highly mobile fiddler crabs (Teal *et al.*, 1992). Data from the Amoco Cadiz indicated shorter recovery times and those from the Exxon Valdez are too recent to evaluate. In general though, data from these spills indicate that the impact is largely dependent upon the type of habitat affected. Shorelines exposed to heavy wave action (especially rocky shores) experience a scouring and cleansing effect which removes much of the accumulated oil, yielding estimated community recovery rates on the order of 5–8 years. Sites in more protected embayments or fjords (especially those with soft or unconsolidated substrata) typically do not experience such scouring and oil remains in these habitats considerably longer, with expected recovery times up to 20 years or longer. See Suchanek (1993) for a review of oil impacts on invertebrate individuals, populations and communities.

Radionuclides.—Radionuclide contamination enters the marine environment both from atmospheric fallout derived from weapons testing programs as well as from more localized coastal nuclear waste dump sites or riverine inputs. Oceanic waters of the northern hemisphere contain considerably greater radionuclide inventory than do those of the southern hemisphere (Noshkin *et al.*, 1978), but coastal habitats experience the greatest potential threat from concentrations of radionuclides dumped at sea. Known ocean disposal sites for nuclear wastes are found virtually exclusively along the near-shore temperate coastlines of the U.S., Japan and in the North Sea (I.A.E.A., 1992). However, recent evidence indicates that enormous radionuclide inventories (possibly larger by many orders of magnitude than any known sites) may reside in the Arctic seas as a result of nuclear weapons and power production in the former Soviet Union. One of the largest known dump sites in the world, the Farallon Islands Nuclear Waste Dump Site (FINWDS), is located just 30 miles west of the Golden Gate Bridge in San Francisco, California. This site contains over 47,500 barrels of radioactive waste in recycled 55 gal drums dumped between 1945–1970. Cores from this site indicate that $^{239+240}$Plutonium levels in sediments may exceed 1,064 times expected ambient background levels (Suchanek, 1987; Suchanek and Lagunas-Solar, 1991). Besides their intrinsic toxicity to marine fauna, these and other radionuclides may bioaccumulate in benthic invertebrates (Schell and Sugai, 1980) and ultimately be transferred to higher trophic levels, including commercial fishes, with potentially serious consequences. Okihiro *et al.* (1993) identify a relatively high incidence of cancerous tumors and lesions in several species of rockfish from a region near the FINWDS. A recent survey of radionuclides in marine organisms from over 300 sites around the U.S. by NOAA's Status and Trends Program shows that, while the levels of some long-lived radionuclides ($^{239+240}$Plutonium and ^{241}Americium) have declined over the past 20 or so years, the levels of ^{238}Plutonium (with a half life of 24,000 years) have increased (Valette-Silver and Lauenstein, 1992).

When considering radionuclide contamination, one of the most significant aspects of impact is the length of time over which environmental effects might last. Some common radionuclides such as ^{137}Cesium have half lives on the order of about 30 years. But others, such as ^{238}Plutonium, have half lives of about 24,000 yr. These radionuclides degrade naturally, but from an ecological perspective, roughly 10 half lives is generally considered to be a reasonable period of time after which no further environmental problems from that source should be expected. With ^{137}Cesium, that impact period might be as long as 300 yr; with ^{238}Plutonium it might be as long as 240,000 yr. Therefore, we must use extreme caution when introducing these types of contaminants into the environment, especially if those elements bioaccumulate through the food chain of nearshore communities.

Dumping radioactive waste at sea is not just a practice of the past. Although there has been an international voluntary moratorium on ocean disposal of radioactive waste at sea since 1985, dumping is once again being reconsidered. At the November 1992 London Dumping Convention, an amendment to permanently ban ocean disposal of radioactive waste (proposed by the Danish delegation) was opposed by the U.S.

delegation. A voluntary temporary moratorium has been extended until approximately July 1993 or beyond, when participating countries will reevaluate the issue. (See note added in proof.*)

3. *Overexploitation*

The status of economically valuable species is especially worrisome. The literature is replete with examples of overexploitation of marine resources (Beatley, 1991; Zedler, 1991). This practice is especially acute for developing countries whose residents must allocate more of their existing resources to survival than do people from developed countries. In places such as Chile, local residents harvest and consume virtually every imaginable source of food from coastal shores including mussels, crabs, snails, limpets, sea urchins, tunicates and algae (personal observation). However, Chile has striven to evaluate and temper its overexploitation of marine coastal resources by establishing a number of coastal parks (Duran and Castilla, 1989).

Developed countries have more modern technology and therefore the ability to exploit a larger proportion of available resources. Worldwide temperate fisheries resources continue to be depleted at an alarming rate. Fin fish, shellfish (including mussels, oysters, crabs, lobsters, sea urchins), and algae are harvested in vast quantities. For example, Chesapeake Bay's indigenous oyster populations are now only *ca.* 5% of their original levels, mostly as a result of overexploitation combined with habitat degradation. Depending on the growth rates of the species involved, recovery could take decades for rapidly growing fishes and centuries for slow growing fishes. Harvesting populations beyond their reasonable maximum sustainable yield causes reductions in future catches. Weakening a population's integrity in this way could make it especially susceptible to stochastic environmental variations such as El Niño events, as likely happened with the California sardine in the 1950s and the Peruvian anchovy in the early 1970s (Thurman, 1991). El Niño events are believed to prevent deep-sea nutrients from reaching surface waters because of alterations in wind patterns and associated surface water flow, causing virtually total collapse of coastal populations of plankton, fishes and birds. Furthermore, overexploitation of fin fish can also have dramatic secondary impacts on community structure (Aronson, 1990; Witman and Sebens, 1992).

4. *Species introductions/invasions*

For over four centuries, natural coastal ecosystems have been altered and threatened from the mostly accidental, sometimes purposeful, introductions and/or invasions of marine species into non-indigenous habitats. Carlton (1987) identifies the major mechanisms by which such inadvertent introductions occur: (1) shipping (organisms fouling hulls and in ballast water) and (2) trans-Pacific transport of commercial shellfish with inadvertent associated "hitchhikers" attached to the shells. He also speculates that the temperate regions along the Pacific coast of North America and Australasia are the most likely areas to receive continued introductions. For example, the U.S. Pacific coast has witnessed nearly 40 introductions of estuarine mollusks, whereas the Atlantic has seen 10 or fewer, and the Gulf coast has had 5 or fewer (Carlton, 1990).

A classic case of competitive displacement by such an introduced species has been documented experimentally by Brenchley and Carlton (1983). The mud snail *Illyanassa obsoleta,* previously abundant in numerous New England coastal habitats, has been competitively displaced by the periwinkle *Littorina littorea,* probably intentionally introduced by European settlers in the early 19th century (Carlton, 1982), altering significantly the structure of those intertidal communities.

Another introduction has garnered special attention in recent years. The well documented spectacular invasion of the Asian clam *Potamocorbula amurensis* (a native of China, Japan and Korea) was likely triggered by the survival of its larvae in ballast water of cargo vessels (see Carlton *et al.,* 1990). First collected in San Francisco Bay in 1986, the abundance of this species exploded to over 10,000/m^2 in some sites within two years! This will likely have dramatic impacts on the San Francisco Bay estuary ecosystem. Some of the expected impacts are: alterations in the energy flow and dynamics of benthic communities by competing with other suspension feeding and deposit feeding infauna; increasing prey resources for mobile predators such as birds, crabs, and fish; reducing phytoplankton standing stock; destabilization of benthic substrata; alteration of the near-bottom suspended sediment load and modification of the sediment redox balance. By affecting the dynamics and stability of the benthic community so dramatically, the existing indigenous populations of this system are clearly threatened; the long-term consequences of this invasion are at present unpredictable.

5. *Global climate change*

Globally mediated processes, although not as tangible or as immediately recognizable as local forms of pollution, will likely contribute significantly to the degradation of coastal marine diversity over the next century. Ozone holes have the potential to produce genetic mutations (Booth, 1990). And, although hotly debated in recent years, there appears to be growing consensus that given our current practices, increased global warming is inevitable, with significant impacts on many global ecosystems, but especially those in temperate environments, including coastal communities. Of all marine environments, the coastal zones will likely be impacted the most by global climate change (Ray *et al.,* 1992). Sea level could rise between 30 and 200 cm in the next century (Beatley, 1991), causing alteration of coastal wetland habitats and unknown effects on resident species. El Niño events provide a "sneak preview" of how associated changing weather patterns, and specifically changes in coastal ocean temperatures, can alter the migration patterns of common nearshore fishes, reduce kelp bed canopy cover and significantly diminish primary productivity that supports entire coastal planktonic based ecosystems.

6. *Human perceptions of marine ecosystems*

One of the major difficulties in preserving the health of coastal marine communities (especially those in subtidal habitats) has been public (and even scientific) perception of the oceanic ecosystem. First, the infamous adage "The solution to pollution is dilution" has been applied liberally to nearshore coastal ecosystems. Once pollutants are added to oceanic habitats they tend to be "out of sight and out of mind." Second, habitat degradation that occurs subtidally is less obvious and more difficult and costly to study than that occurring in terrestrial or even intertidal habitats. Also, because of the lower proportion of endemic fauna and flora found in marine coastal habitats, conservation efforts are also not as strongly applied to these regions (Salm and Clark, 1984). That is, because of coastal current patterns and the ability of many marine species to disperse using planktonic larvae, those species are often not limited to as small geographic regions as terrestrial species. While biogeographic provinces exist in the marine environment, their boundaries are not nearly as distinct. As such, in the face of disturbance, these marine species can repopulate over much broader geographic areas (100s or 1,000s of kilometers) than can many species in terrestrial habitats. Hence, it is perceived that conservation measures do not need to be as strictly enforced in coastal regions.

In general, the conservation and management of temperate coastal marine communities are often either not taken as seriously as for other habitat types, or the communities are not as well known, especially by European and Australian researchers, for example. It is rather instructive to note that, in a recent treatise on "The Scientific Management of Temperate Communities for Conservation" from the British Ecological Society, the one paper in twenty one that dealt with the "Management of Coastal Communities" (Gray, 1991) emphasized almost exclusively terrestrial components, with only passing mention to marine communities.

While considerable attention has been focused recently on biodiversity losses in tropical wet and dry forests, it is clear that the coastal zone environment is being altered just as rapidly (Beatley, 1991). And, although tropical rain forests have more species, the marine environment has about double the number of phyla (Ray, 1988).

Although larger fauna (mammals, birds and reptiles) often enjoy protected status, typically no other coastal marine species (particularly marine invertebrates and algae) are registered on coastal state or federal endangered or threatened species lists, even though invertebrates and algae comprise the bulk of species in these communities. Ironically, freshwater mollusks and crustaceans have abundant listings. The primary difficulty is in recognizing the decline of populations and communities (1) that are not normally visible, (2) for which our knowledge is limited and (3) for which we maintain no ongoing monitoring program. A special symposium addressing issues of invertebrate conservation (including coastal marine species) entitled "The Crisis In Invertebrate Conservation" was held at the American Society of Zoologists in Vancouver, B.C. in Dec. 1992, with the symposium papers published in the *American Zoologist* in 1993.

7. *Legal complexities*

One of the most difficult aspects to deal with in assessing the magnitude and significance of coastal habitat degradation is the fact that litigation not only drives much of the research on pollution in coastal communities, but it also often restricts the flow of scientific data. This is typically experienced in high profile cases such as the Amoco Cadiz and Exxon Valdez oil spills, where major corporate finances and criminal and/or civil charges are at stake. It is not uncommon for scientific data to be locked up or significantly restricted for 5–15 years while opposing legal counsels litigate and appeal decisions. Not only are colleagues working on opposing sides forbidden to discuss protocols or results, but often researchers working for two branches of the same federal agency are not allowed to communicate about data that are stamped with messages like "Attorney Work Product-Prepared for Counsel Only-DO NOT CIRCULATE-DO NOT PUT IN UNPROTECTED FILES."

With these kinds of restrictions, it may be a decade or more before real impacts are known, too late to have positive benefits on similar disturbance events in the short-term. And, in some cases the data are locked up forever, especially if funded by corporate interests. We need to hasten and simplify the process of data release so that valuable impact studies can have more immediate value to the scientific community and to the environment.

SUMMARY OF THREATS AND CONSEQUENCES

Whatever the causes, the ultimate cumulative effect of the stresses to the marine environment listed above is the potential elimination or significant diminution of a particular local or regional genetic stock, species, or effective breeding population of individuals. When one or several species are eliminated from a community, this will change the established trophic (food web) dynamics, the important species-species interactions that define the nature and structure of the community.

The removal of one species can cause secondary or indirect effects on species in other trophic levels, sometimes several trophic levels at once, and even influence physical factors. But, the important component of this effect is *which* species are impacted. Paine (1966) developed the concept of the "keystone species," a species that has a disproportionate influence on the community than would ordinarily be expected by its abundance alone. While the original concept referred to keystone predators, it has been expanded to keystone resources and keystone mutualists (Terborgh, 1986). Any species that holds such an important or "keystone" role in a community that is impacted by habitat degradation or is unable to reproduce or compete effectively, will undoubtedly alter the structure of the community. Therefore, knowledge of community processes and identification of "keystone species" can be used to guide conservation efforts.

A classic example of overexploitation of marine coastal mammals by Russian and American fur traders undoubtedly had such an altering effect on nearshore marine communities. Sea otters were virtually eliminated from regions of the Aleutian Islands during the 1700s and 1800s and by the twentieth century were nearly extinct (Riedman and Estes, 1988). When otters were abundant they acted as keystone species by consuming large numbers of sea urchins, which in turn resulted in the proliferation of their food source, kelps (Estes and Palmisano, 1974). Kelps help to dampen wave action, causing increased sedimentation nearshore, producing more soft sediment environments and changing the nature of dominant benthic organisms from species adapted to hard substrata to those adapted to soft substrata. Without otters, sea urchins proliferate, kelp populations are low, wave action is not as dampened, soft sediments do not as readily accumulate and hard substratum organisms predominate.

A more recent view of this process involves the concept of "trophic cascading" or "top-down" *versus* "bottom-up" forces that drive and structure ecosystems (see Paine, 1980; Carpenter *et al.,* 1985; Menge, 1992; Strong, 1992). Top-down forces imply that some upper trophic level species (predators or herbivores) engage in extreme consumption that influences significantly all of the species or resources in the trophic levels below them. An ecosystem controlled more by bottom-up forces would be one which is controlled by the abundance or level of resources such as nutrients, whose influence then filters up to higher trophic levels. In either case, effects may cascade up or cascade down to bring about significant alteration or control of ecosystem structure. In addition, it appears that the "strength" of these interactions is also of utmost importance in determining community structure (Paine, 1992). There is still ongoing debate over which types of forces more typically contribute to structuring ecosystems, but the point is no matter which level may be affected by environmental degradation (resources or trophic interactions), there could likely be dramatic alterations to ecosystem structure and function. In this case, the result may not be just a reduction of individuals within a particular species, but a significant unpredictable change in the entire system. For example, although the diverse mussel bed community described by Suchanek (1992) has been documented, and we know that a few particular species in this complex contribute significantly to the long-term stability and integrity of the mussel bed structure through mutualistic interactions (Suchanek, 1985; Seed and Suchanek, 1992), we know virtually nothing about species-species interactions among the rest. We should not be willing to "experiment" with nature by disrupting such a complex and poorly known system by creating unpredictable results before we understand more fully the consequences of our actions.

DISCUSSION AND CONCLUSIONS

Measuring biodiversity

Important elements of biological diversity that are typically considered when dealing with issues of biodiversity are: genetic diversity, species diversity, habitat diversity, community diversity, and ecosystem diversity. All are relevant to the issue of threats to biodiversity in temperate marine coastal habitats. For most people, the term "biodiversity" is an aesthetically satisfying buzzword, easily incorporated into laymen's (and legislators') appreciation of the world around us, and has gained widespread popularity among both the general public and the scientific community. A more serious problem exists, though, when one tries to quantify biodiversity. Biodiversity tends to be a nebulous concept and attempts must be made to make its measurement more rigorous. One of the difficulties in evaluating coastal biodiversity, or any biodiversity question for that matter, is the fact that currently we have no common "yardstick" to use in evaluating biodiversity.

Many different types of measures have been used to evaluate the abundance and diversity of organisms, many framed in the context of "biodiversity." Some of the more common approaches used to evaluate the relative health of coastal regions are: *numerical abundance* of individual taxa (number of individuals of one or of all species present), *species richness* (total number of species), *diversity* (using specific formulae for the relative abundance of individuals of each species) and *evenness* (a measure of how evenly distributed individuals are among all species). Another aspect of biodiversity that has been given serious consideration, especially with respect to the marine environment, is the taxonomic *relatedness* of species. In this context, there is "broader" diversity in the marine environment than on land (Thorne-Miller and Catena, 1991). That is, terrestrial environments may have more species, but they are more closely related. In the marine environment there are more higher order taxonomic differences, at the level of phyla, orders, families, etc. Therefore, there are larger genetic differences that are represented.

Although many yardsticks are used, some type of diversity index that incorporates both the numerical abundance of individuals and the total number of species is probably a reasonable tool to compare species biodiversity over time and/or space. We should, however, be careful to interpret this measure of biodiversity correctly. Higher diversity does not necessarily mean higher intrinsic value. The greatest benefit in using a diversity index is derived when it is used to compare similar communities or habitats in different regions, or the same community or habitat at two or more points in time. The most commonly used species diversity indices are the Shannon-Wiener Index (several versions) and Simpson's Index. Most general ecology textbooks provide the details on calculation of diversity indices and Southwood (1978) provides a reasonable overview of the topic of community diversity and how one should use it in the context of measurement and comparison.

Individual responses to stressed environments

While the ultimate impacts on biodiversity are typically documented at the population or community level, the proximate causes are actually impacting *individuals* within those populations. At the individual level each species has a set of specific physiological tolerance limits to variations in natural environmental parameters (*e.g.*, temperature, oxygen, salinity) as well as to human-altered parameters or pollutants (*e.g.*, thermally elevated water, increased sedimentation, copper, oil, radionuclides). These physiological tolerance limits are expressed in terms of the organism's ability to adapt to variations in those variables in the environment. Hypothetically, if there were only one environmental variable to which an organism was exposed, there would be an increasingly limited range of that variable under which that organism could survive, grow and reproduce. Organisms cannot grow unless they can survive and under most situations organisms will reproduce only under a subset of the conditions under which they can grow. This limited set of conditions for each life function, depending on its response to an environmental variable, could be expressed by the zones in the one-dimensional resource diagram in Figure 1A.

Adding a second environmental variable would yield a set of progressively smaller circles (combinations of environmental variables) in which the organism could survive, grow or reproduce (Fig. 1B). Adding a third environmental variable would logically produce a small volume, say a sphere (it could be a box or any other shape) representing the combination of environmental variables permitting reproduction, within a larger sphere representing growth, within yet a larger sphere representing those conditions that would permit survival (Fig. 1C). Outside of the conditions that define the survival sphere, the organism dies. As we add the other myriad natural environmental variables (plus introduced stresses and pollutants), we would produce an n-dimensional space that is not only more difficult to represent on a two-dimensional printed page, but is also more representative of conditions in which it becomes increasingly difficult for organisms to reproduce, grow or even survive. This is precisely the difficulty that most temperate coastal communities face in those habitats subjected to multiple stresses. The multiple threats addressed in the bulk of this paper produce a situation where there are fewer and fewer coastal habitats that will permit survival, let alone allow for growth or reproduction.

STEPS TO INSTITUTE AND MAINTAIN MARINE COASTAL HABITAT PROTECTION

Reactive management is insufficient to meet increasing needs for protection of our coastal environments. We need to institute sensible long-term strategies for comprehensive management plans to protect our

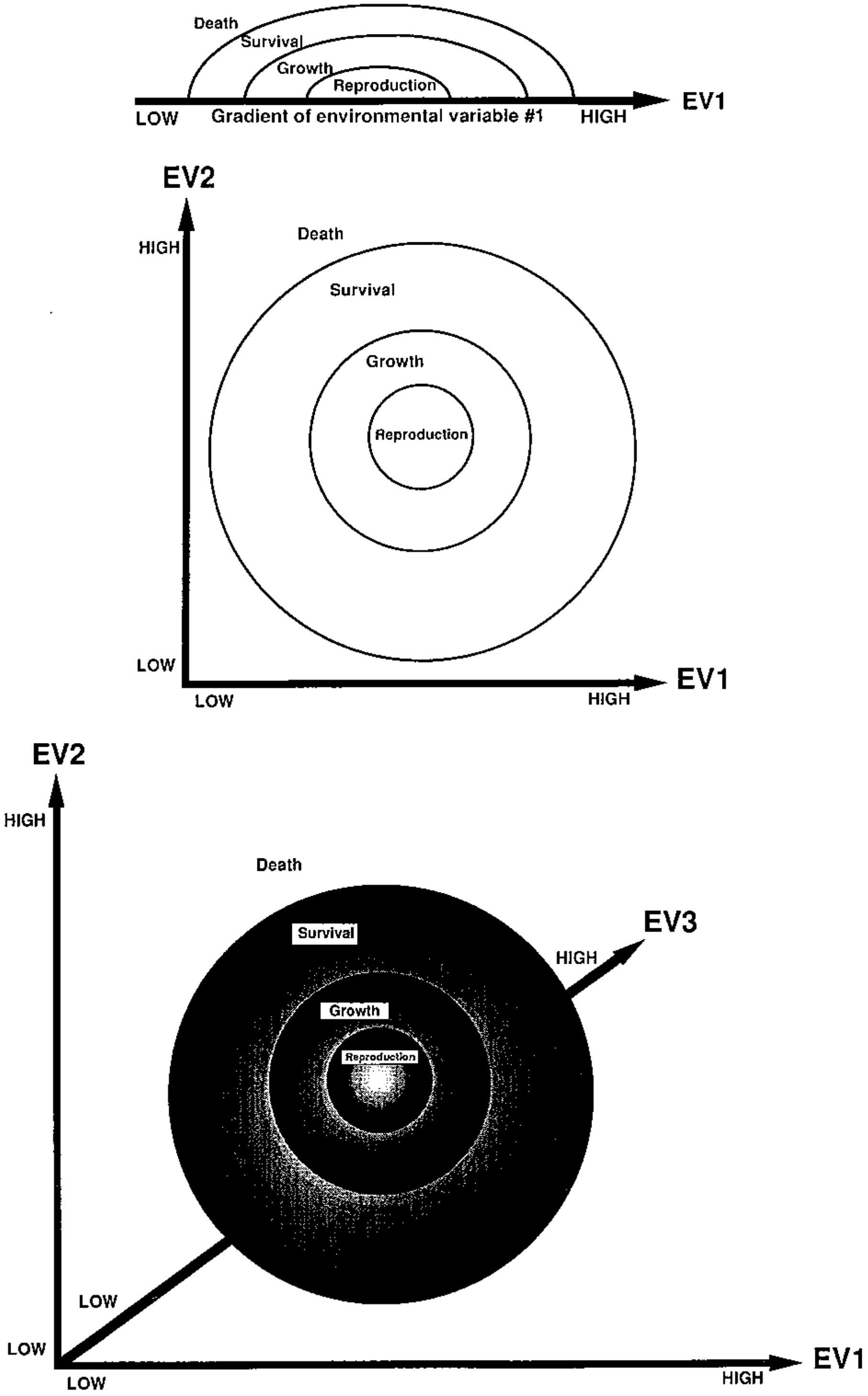

FIG. 1. Hypothetical example of physiological tolerance limits and restriction of life functions to one environmental variable (1A), two environmental variables (1B) and three environmental variables (1C).

coastal biodiversity resources. Benefits of these resources include not only the integrity of the ecological communities and quantitative diversity of species discussed above, but the multitude of economic, cultural, social, educational and aesthetic benefits that we as humans derive from their very existence.

Environmental policy analysts, agencies and legislators are crying out for more meaningful scientific information with which they can formulate coastal policies in the form of resource management plans and legislation (Douglas, 1992*a, b*). To begin this process we should dedicate resources to coastal population, community and ecosystem research. An enormous amount of recent scientific attention, funding and research has been focused at the molecular and cellular level and not enough on basic descriptions of marine communities or an understanding of ecosystem function. Consequently we are not well prepared to evaluate the impact of acute point-source perturbations or long-term chronic non-point-source perturbations on the health and function of marine coastal communities. We need first to evaluate the current levels of resources present in these environments and second to understand the dynamics of processes that control populations and communities before we can predict or modify ongoing short-term and long-term changes that are affecting coastal diversity.

Inventory/research

Our first step should be to provide a description of what exists, an inventory. Then we must continue to monitor changes in both the existing populations and in potential threats to those populations such as pollutants and major changes in the physical, chemical and biological nature of the local habitat. This is not a recommendation for mindless monitoring of every environmental parameter we can measure. Rather, by first committing some limited resources to understanding how these ecosystems function, we should be able to choose several indicator species (sentinel species or keystone species) or environmental parameters that will provide us with an ongoing measure of the relative health of a given community.

We should not be preoccupied with maintaining some particular level of diversity or set of species in a community. If there is one message to derive from this paper, it is that the most critical part of maintaining biodiversity is maintaining the dynamic set of interactions that define what that ecosystem is and how it functions. What is critical in these ecosystems appears to be the nature and strength of complex interactions between species; we believe that is what maintains the integrity and therefore the long-term stability of these communities.

Several excellent programs have been initiated to monitor levels of biologically relevant pollutants (those which are acutely toxic and/or which bioaccumulate) in nearshore environments. The National Mussel Watch program was started by the National Academy of Sciences in 1976 to monitor levels of anthropogenic pollutants in U.S. coastal waters (Farrington, 1983) and continues today. This program takes advantage of the fact that bivalves are extremely efficient filter feeders, and represent excellent sentinels of pollution as they bioconcentrate chemicals from the environment 100 to 100,000 times ambient levels. In the late 1970s and early 1980s the National Oceanic and Atmospheric Administration (NOAA) also started a Strategic Assessment Program (under the Ocean Assessments Division) to conduct comprehensive, interdisciplinary assessments of coastal resource use (Ehler and Basta, 1982). Included in this program are the following programs: National Coastal Pollutant Discharge Inventory, National Estuarine Inventory, Living Marine Resources Inventory and the Status and Trends Program. These and other similar programs should be encouraged and funded liberally.

Protection

Only by enforcing strict protection for our valuable coastal resources can we hope to stem the tide of declining biological resources and diversity. There are several types of protective designations that have been assigned to coastal marine habitats in the United States and elsewhere. As an example, I provide a list of International, National, State and Institutional sites from California that have been established to protect coastal marine habitats and associated biodiversity (jurisdictional agency in parentheses). (1) *International*: Biosphere Reserves (UNESCO) and World Heritage Sites (UNESCO), (2) *U.S. National*: Estuaries (EPA), Estuarine Reserves (NOAA), Marine Sanctuaries (NOAA), Natural Landmarks (NPS), Important Habitat Areas (USF&WS), Areas of Critical Environmental Concern (BLM), Wilderness Preservation Areas (USF&WS, USFS, BLM and NPS), Natural Research Areas (NPS) and Wildlife Refuges (USF&WS) as well as (3) *California State* mandated: Areas of Special Biological Significance (WRCB), Marine Life Refuges (CDF&G), Preserves, Reserves (CDF&G), Wildlife Areas (CDF&G), Wildlands Areas (CDF&G), Underwater Parks (Dept. of Parks & Rec.) and (4) *Institutional* sites: such as Audubon sanctuaries, university research sites and other Preserves or Easements (California Nature Conservancy).

Although protective status is a good first step, it does not directly confer effective protection. We must provide the necessary resources to maintain a certain level of protection to these already established sites so that further habitat degradation and loss of diversity does not continue at such an unacceptable rate. With this effective protection, plus ongoing monitoring and research on ecosystem function, we will have the best opportunity to preserve the valuable biodiversity resources that exist in coastal temperate marine habitats worldwide.

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*NOTE ADDED IN PROOF

Good news. At the London Dumping Convention in November 1993 the United States, along with 36 other nations, voted to permanently ban the disposal of nuclear wastes at sea. No other countries voted against the ban, but five countries abstained: Belgium, Britain, China, France and Russia. The ban covers 71 countries that signed the 1972 London Convention; each has 100 days to opt out of the agreement.