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Climate Change, Human Impacts, and Community Structure

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ABSTRACT

Since the Industrial Revolution, anthropogenic influences have assumed a major role that will shape future global climate change. Additionally, evidence is emerging that human impact on climate can be detected circa 8,000 BP in carbon dioxide anomalies temporally correlated with the beginning of forest clearing and circa 5,000 BP in atmospheric methane levels occurring at the time of initial wet rice cultivation. How will future elevated seawater temperature, changes in patterns of precipitation, and the frequency and distribution of major storm events unfold? How will they affect marine life? Most organisms will likely adapt by altering distribution patterns. But will rates of extinction increase? How will such events at the species level forced by climate change translate into alterations in community structure? We must also expect greater fragmentation of the habitat as human population density increases in coastal areas. Finally, alien species present serious threats to habitat stability. In this paper, I will focus on three case studies each involving kelp communities that reveal some of the complex issues inherent in studies of biodiversity and its linkages to climate change and human impacts.

Keywords: Kelp communities, Global warming, Habitat fragmentation, Invasive species

INTRODUCTION

On a globally-averaged scale, sea level has risen approximately 10–20 mm over the past century. The change in sea level that is observed globally is primarily attributed to thermal expansion of seawater accompanying increased seawater temperature and changes in the amount of water bound in landlocked states such as glaciers [1]. Much of this change is driven by anthropogenic forces such as carbon dioxide emission through the burning of fossil fuels and the clearing of forests, and by increases in levels of methane and nitrous oxide also resulting from human-associated activity. For example, atmospheric levels of carbon dioxide have increased 31% since preindustrial times and half of this increase has occurred in the past 40 years [2] [Fig. 1]. Evi-

dence is now emerging that anthropogenic-driven global warming may have preceded the Industrial Revolution [3]. Recent analyses of cyclic variations in carbon dioxide and methane show departures from levels predicted by Earth-orbital changes. Carbon dioxide began an anomalous increase 8000 BP at about the time of early agriculture in Eurasia and forest clearing by fires. A departure in expected methane levels is first observed about 5000 BP near the initiation of wet rice farming. Interestingly, decreases in atmospheric carbon dioxide resulting in the Little Ice Age (1300–1900 AD) may be linked to human plagues. High mortality may have left abandoned farms and villages leading to the growth of new forests that sequestered carbon dioxide later to be returned to the atmosphere as human population sizes increased following plague events [3].

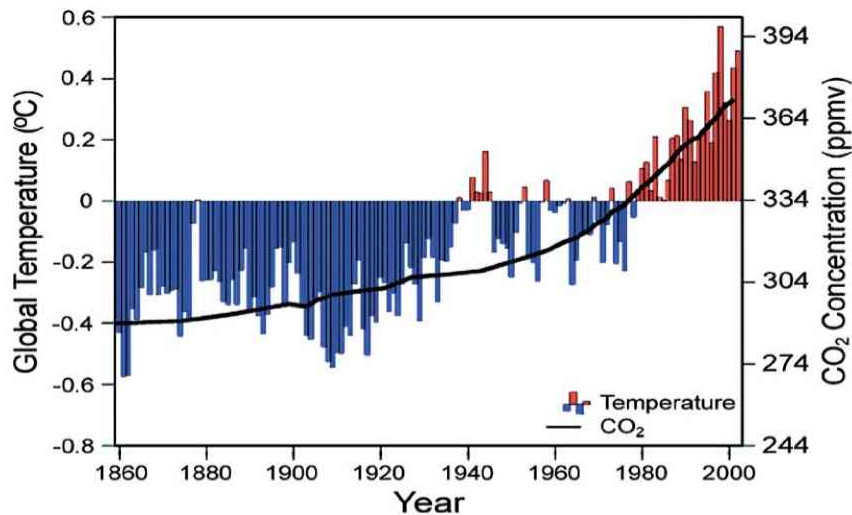


Fig. 1 Time series of departures from the 1961 to 1990 base period for an annual mean global temperature of 14.0°C (bars) and for a carbon dioxide mean of 334 ppmv (solid curve) during the base period. [Ref. 2]

Increases in concentrations of greenhouse gases such as carbon dioxide, methane, and nitrous oxide contribute to warming of the lower atmosphere and increasing seawater temperature. But the impact extends further because “global warming” also results in removal of water vapor from land and, concomitantly, increasing levels of water vapor in the atmosphere. Water vapor is itself the major greenhouse gas. Consequently weather patterns change as droughts increase in frequency and severity from drying of the land and, simultaneously, precipitation and storm patterns vary due to increased atmospheric water vapor [2] [Fig. 2].

How this complex set of changes will unfold is a major focus of environmental science. Similarly, how these changes in the abiotic environment will

affect human activity and marine life is a major driving force in contemporary marine and conservation biology. Approximately 40% of the world's human population lives within 100 km of the sea [4]. One must expect loss of coastal land and low-lying islands due to factors such as inundation and erosion [Fig. 3]. As human population grows, the pressure on coastal areas will only increase. The combination of rising sea level and human population increase will intensify pressure for conservation practices that will preserve resources at the intersection of land and sea.

Increasing seawater temperatures can be expected to affect patterns of reproduction and dispersal of many marine organisms. For example, sex determination in some fish [5] and in all sea turtles [6] is sensitive to temperature. As temperature increases,



Fig. 2 Soufriere, St. Lucia Island, Caribbean in 1999 after hurricane. Note heavy sediment load in water, substantial beach erosion, and damaged buildings at the shoreline.



Fig. 3 Low-lying motu, Taha'a Island, French Polynesia.

will sex ratios at birth be altered, especially in the cases of those species with geographically restricted breeding or nesting sites? How would any such shifts translate into changes in population structure and, ultimately, community dynamics? Annual mean seawater temperature as well as maximum and minimum temperatures have key roles in initiating and modulating reproductive events for many species of marine invertebrates as well. Environmental signals such as temperature are documented to be important in triggering activation of gonadal processes [7] and also downstream in modulating maturation and spawning [8]. Will species adapt to slowly rising temperatures and retain in general their present ranges or will species adapt by altering their geographic distributions to remain in near similar temperature ranges over time? Will some species face extinction as their environment changes?

Attempting to gauge the importance of extinction rates attributable to climate change raises two problems common to all studies of extinction. The most fundamental issue is one of taxonomy. Biologists cannot study extinction without knowing the taxonomic status of the lineage in question. Our understanding of basic taxonomy in most groups of marine organisms falls drastically behind similar knowledge concerning terrestrial taxa. Importantly, the completeness of our knowledge varies dramatically from group to group as well. The depth of taxonomic understanding in many groups found even in easily accessible habitats remains sadly underdeveloped [Table 1]. And this shortfall is more glaringly obvious once we leave the familiar coastal habitats and move to less explored regions of the sea [9].

Another source of confusion lies in how extinc-

tion is defined. For example, a species may become globally extinct, locally extinct, functionally extinct, or commercially extinct, depending on the context in which it is being studied [10]. Technically, extinction should best be reserved for the complete elimination of a species. It is often convenient, however, in studies focusing on a region to describe a species that once but no longer occurs in that region as extinct. Similarly, a species may be described as functionally extinct when its abundance falls to a level such that the species no longer manifests the same role in ecosystem function as it did during a prior time. Commercial extinction occurs when a species is reduced in population size by human activity to the point that it is no longer an economically viable product. If we restrict our view of extinction to the global variety, then the known number of extinctions of marine birds, mammals, and invertebrates in historical times is small [10]. These data, however, are almost certainly underestimates due to insufficient knowledge of the diversity present, taxonomic status of known specimens, and limited sampling.

One example of the extinction of a marine organism in historical times is the case of the Atlantic eelgrass limpet, *Lottia alveus alveus* [11] [Fig. 4]. The last known specimen was collected in 1929. In the 1930s, the eelgrass *Zostera marina* found along the Atlantic seaboard of America as well as in Europe underwent a drastic and sudden decline. With the decimation of euryhaline populations of eelgrass came loss of habitats for juvenile fish and invertebrates, increased siltation, and loss of food resources for migrant waterfowl and the green sea turtle. The death of euryhaline populations in the 1930s was

Table 1 Examples of the magnitude of underdescribed biodiversity among marine invertebrates in familiar and easily accessible marine environments. [Modified from Ref. 9]

Site	Taxon	Number of Undescribed Species out of Total Collected in the Taxon
Gulf of Mexico	Copepods (haracticoids)	19–27 of 29 (shelf site, 18 m)
New Guinea	Snails, sea slugs	310 of 564 (one lagoon)
Philippines	Snails, sea slugs	135 of 320 (one island, multiple sites)
Georges Bank	Marine polychaete worms	124 of 372 (shallow shelf, multiple stations)
Hawaii	Marine polychaete worms	112 of 158 (6 liters of coral reef sediment, one island)
Great Barrier Reef	Marine flatworms (polyclads)	123 of 134 (two islands)



Fig. 4 Shells of the eelgrass limpet *Lottia alveus alveus*. [Museum of Comparative Zoology]

likely linked to an infection by the marine slime mold *Labyrinthula* sp. that was confirmed as the agent in a later disease outbreak occurring in the 1980s [12]. Some correlation exists, at least in the European outbreak of the 1930s, between eelgrass wasting and elevated seawater temperature [13]. A relationship, however, between outbreaks of wasting, occurrence of the marine slime mold, and rise in seawater temperature likely exists though it has not been incontrovertibly proven. Hyposaline environments served as refuges for the eelgrass whereas euryhaline populations were affected with the disease. Unfortunately, the Atlantic eelgrass limpet lived only on eelgrass in euryhaline environments so it faced extinction due to the wasting disease eliminating its habitat. The case of the Atlantic eelgrass limpet is complex and it points to the difficulties that arise in establishing linkages between climate change and altered patterns of biodiversity.

The complexities in establishing interconnections

among climate change, human impacts, and community structure are manifest. The three case studies highlighted below point to the multidisciplinary efforts that are required to understand the impacts of human activity on marine biodiversity.

CASE STUDY No.1: KELP COMMUNITIES AND CLIMATE CHANGE

Along the Pacific coast of southern California the health and distribution of *Macrocystis pyrifera*, the giant kelp, is impacted by the occurrence of El Niño and La Niña events as well as decadal regime shifts [Fig. 5, 6]. In El Niño years, nutrient-poor warm waters invade the kelp community and the biomass of *M. pyrifera* decreases. In La Niña years, colder nutrient-rich waters are associated with high rates of kelp production. Abundances of important kelp community architects such as sea urchins and understory macroalgae decrease and increase as well

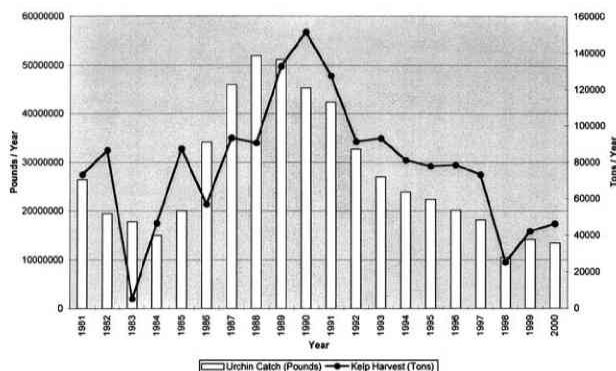


Fig. 5 California yearly urchin and kelp harvest, 1981–2000. [California Department of Fish and Game]

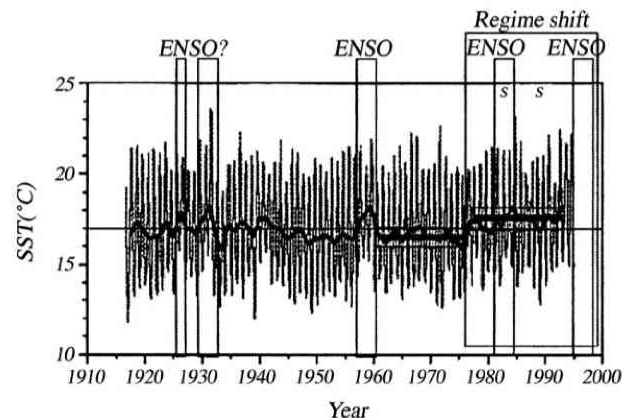


Fig. 6 Recent decadal to annual thermal sea surface temperatures for southern California. [Ref. 15]

(though differently) with these ENSO events. Even with no change in El Niño amplitude, global warming is likely to result in greater extremes in climate events. El Niño warming lowers kelp productivity and, hence, reduces health of the kelp-based ecosystem. La Niña cooling, though conducive to high productivity, is also often associated with strong storm impacts that affect community structure. These storm-related impacts, however, are short in duration and a rapid recovery of the kelp system follows [14].

The historical stability of this kelp community was based on a series of predators including the sea otter, spiny lobster, and carnivorous fish that controlled population levels of herbivores, especially sea urchins that are the primary grazers on kelp [15]. Fur hunters eliminated otters from this region in the early 1800s [16]. For some time, alternate predators such as the spiny lobster and sheephead kept urchin population sizes within control. But eventually with increased fishing pressure the numbers of these predators decreased and predation pressure on urchins was relaxed, resulting in large-scale destruction of kelp forests and replacement with crustose algal - urchin barrens. With the loss of predators to control urchins, the dynamics of the southern California kelp communities sway primarily on climate variability and on cycles of urchin densities modulated largely by urchin-related diseases.

Urchins can survive in barrens without apparent starvation, though their reproductive output is compromised compared with those in a kelp dominated community.

The health of the kelp communities in southern California has deep economic implications as well. Not only is kelp harvested for commercial purposes, but so are urchins, abalone, lobsters, and a host of fish found in abundance in kelp forests. For example, the urchin fishery in southern California is based primarily on the red sea urchin, *Strongylocentrotus franciscanus* [17]. As seen in Figure 5, the urchin catch tracks closely with kelp abundance, which in turn, is correlated with climate state. In this example, climate affects not only community structure, but also the availability of commercially important organisms such as kelp and sea urchins.

CASE STUDY No.2: KELP COMMUNITIES AND HABITAT FRAGMENTATION

A striking example of how human alterations to the environment can directly affect kelp communities comes from the elegant studies done at Hokkaido University in the Faculty of Fisheries by Professor Katsuhiko Matsunaga [18, others]. Matsunaga and his team sampled a series of sites around southern regions of Hokkaido Island [Fig. 7]. All sites selected should have been favorable habitats

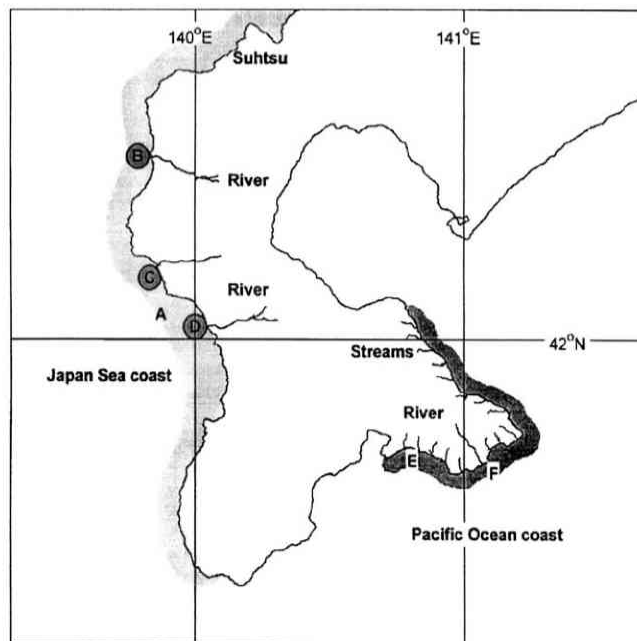


Fig. 7 Sampling locations off Hokkaido Island, Japan. The Tsushima warm current flows through both sides of the southern region of the island. Light shaded area: crust-dominated community. Dark shaded area: kelp forest community. [Ref. 18]

for kelp forest development. Yet, these investigators found on the Japan Sea coast large extents of crustose coralline algae instead of kelp, exceptions being near the mouths of rivers where kelp dominated. In a parallel series of sites on the Pacific Ocean coast, kelp dominated and crustose coralline algae were absent. Temperature shifts and urchin abundances did not explain these observations.

The association of kelp communities with sites of riverine input to the Sea of Japan led these investigators to hypothesize that chemicals present in the forest sources of water may promote kelp dominance and inhibit coralline algal presence. They tested in the laboratory the effects of humic substances on the growth of tetraspores of the crustose coralline *Lithophyllum* spp. and found significant inhibition of tetraspore growth by both fulvic and humic acid extracted from forest soils [Fig. 8]. In a companion set of experiments, several sources of exogenous iron were added to seawater and the effects on oogonium formation in the kelp *Laminaria religiosa* were measured. Significant enhancement of growth levels in controls was observed in fulvic-iron complex and less so, but still significant over controls, with addition of amorphous iron [Fig. 9]. The authors hypothesized that at the Sea of Japan sites suburban development creating extensive impervious barriers to freshwater runoff coupled with deforestation accompanying human encroachment at the land - sea interface limited riverine discharge of bioactive substances. In turn, the absence of these substances depressed oogonium formation thereby reducing the kelp population and simultaneously released crustose algae from the naturally occurring re-

pression of tetraspore germination that accompanies the presence of substances in forest runoff.

This fundamental research by Matsunaga and his group led to important new management practices in forestry and fisheries biology in parts of northern Japan [19]. Inputs of biologically active molecules from forested watersheds help maintain healthy kelp communities and retard the formation of crustose algal - urchin barrens [*Isoyake*]. Increased yields follow of commercially important stocks such as herring that depend on kelp forests for food, shelter, and spawning grounds.

CASE STUDY No.3: KELP COMMUNITIES AND INVASIVE SPECIES

The kelp community in the Gulf of Maine was originally structured by kelp [*Laminaria* spp.], one species of sea urchin [*Strongylocentrotus droebachiensis*], and large predatory groundfish such as cod. These groundfish served the function of apex predators controlling urchin population size in a fashion similar to that of sea otters in northeast Pacific kelp forests [15]. Extensive fishing for cod and other groundfish began in the 1930s. With heavy fishing pressure and lack of adequate regulation of the fishery, the stocks of cod diminished drastically. Much has been written about the collapse of the cod fishery and of its economic and societal implications. Less well appreciated are the effects of reduction in cod on community structure of Gulf of Maine kelp forests. With loss of this apex predator, the food web was altered and urchins, lobsters, and crabs all

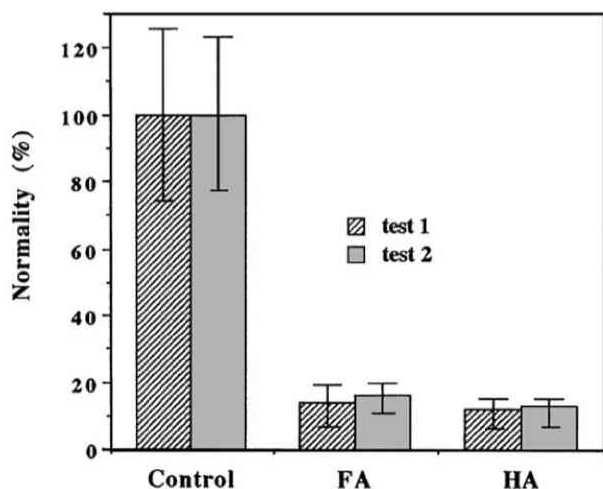


Fig. 8 Effect of humic substances on tetraspore growth of *Lithophyllum* spp. FA: fulvic acid, HA: humic acid. [Ref. 18]

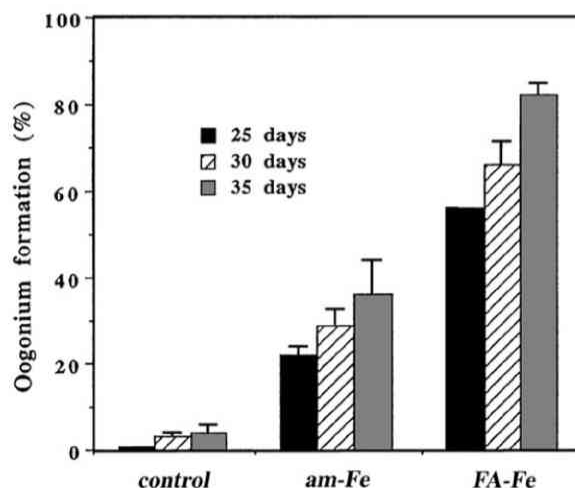


Fig. 9 Effect of different iron species on oogonium formation in *Laminaria religiosa*. am-Fe: amorphous iron, FA-Fe: fulvic-iron complex. [Ref. 18]

increased in abundance. By the mid-1960s, the benthos was more a mosaic of kelp beds and urchin barrens [15] and by a decade later a similar mosaic was observed off Nova Scotia [20]. By the 1990s, kelp abundance reached its lowest extent while urchin barrens and their associated coralline algal mats grew and merged to be dominant elements of the benthos. The situation was similar in Nova Scotia except that urchin populations there were affected by bouts of disease that reduced their numbers in an oscillatory fashion [21]. A sea urchin fishery began around 1987 reaching a peak in 1993–94 [17]. During this period urchin stocks became depleted and kelp forests recovered. Crabs assumed the role of apex predators in regulating urchin population size [15].

This delicate balance was disrupted by the introduction of two important alien species: a bryozoan and a green alga. Structure of the benthic community shifted away from kelp forests and patches of urchin barrens with crustose algae toward fields dominated by introduced species of macroalgae. The bryozoan *Membranipora membranacea*, common to Western Europe and the Pacific Coast of North America was first reported from the Isles of Shoals in the Gulf of Maine in 1980s [22]. *M. membranacea* forms extensive encrustations on algal fronds [Fig. 10]. Importantly, colonies grow rapidly and occur often in sufficient numbers to cause fronds to become brittle and break resulting in mortality of adult kelp populations [23, 24, 25]. The benthos becomes a mosaic of kelp forest, barren, and fields of introduced algae [25], the most important of which

is a species of green alga, *Codium fragile* ssp. *tomentosoides*. This subspecies was introduced from Western Europe to Long Island in 1956 [26] [Fig. 11], but is now common in the Gulf of Maine [24]. New kelp recolonize gaps created by mortality induced through bryozoan overgrowth. But when the introduced green alga is present, it prevents kelp recolonization [25]. Furthermore, manipulations of herbivores document that herbivory reinforces dominance of the introduced green alga [25]. In regions of Nova Scotia, *Codium fragile* ssp. *tomentosoides* has become a dominant macroalgal component of the rocky subtidal [21]. Laboratory studies conducted over the course of 11 months aimed at examining the dietary preferences and effects in *S. droebachiensis* [Fig. 12] on *Laminaria* spp. and *Codium fragile* ssp. *tomentosoides* food sources revealed that the urchins preferred kelp over the green alga. Importantly, urchins fed only the green alga over an annual cycle failed to have gonadal development compared with urchins fed on kelp or on a mixed diet of kelp and the green alga [21] [Fig. 13]. The authors conclude that urchins at moderate densities will graze kelp over the green alga when both algae are present. One result will be heightened removal of kelp and enhancement of barren regions and patches of green algae.

These studies point to the rapid shifts in community structure and dynamics that can result from introductions of alien species. Such ecological disasters are more likely to occur in regions lacking depth in species richness such as that observed in



Fig. 10 The invasive bryozoan *Membranipora membranacea*. Colonies overgrowing the kelp *Laminaria* sp. at Nahant, Massachusetts. The cylindrical bodies projecting upward from these encrusting colonies are “tower cell kenozooids”, enigmatic highly modified polymorphic zooids that are known to occur only in this species of bryozoan.



Fig. 11 *Codium fragile* ssp. *tomentosoides* a green alga invasive to the Gulf of Maine. This species successfully outcompetes kelps for space.

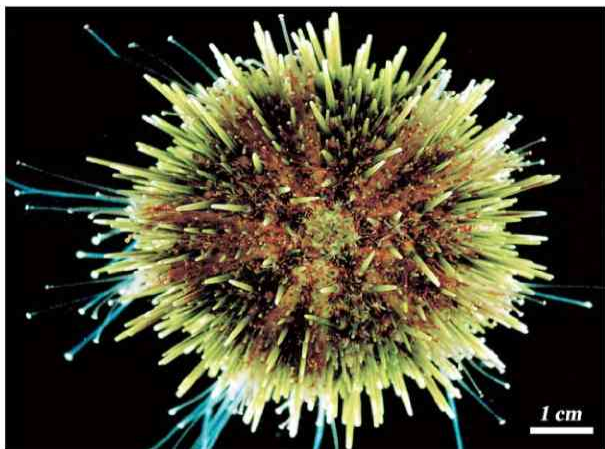


Fig. 12 *Strongylocentrotus droebachiensis*, the naturally occurring sea urchin found in the Gulf of Maine.

the Gulf of Maine.

CONCLUSIONS

1. Addressing the adverse effects of human impacts on the marine environment is dependent on gauging the types and magnitudes of changes that can be predicted to occur. Such efforts are inherently multidisciplinary and require a merger of activities between the physical and biological sciences.
2. The cornerstone of the biological component of this effort resides in taxonomy. The ability to identify with precision individual species is the foundation on which rational conservation and management efforts can be generated. In this context, it is necessary to build reference collections across phyla, on a regional basis, and from the diverse array of habitats. Such collections need to include digital information as well as actual specimens to enable remote access and to facilitate updating as the database expands.
3. Understanding how environmental change acting at the level of individual species is translated into alterations in community and ecosystem dynamics is the major challenge we face in "The Dawn of a New Natural History".

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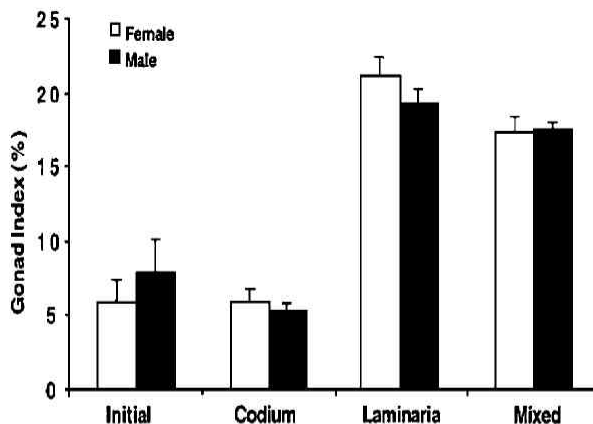


Fig. 13 *Strongylocentrotus droebachiensis*. Gonad index of females and males at start of experiment (Initial) and in three diet treatments at end of the experiment. [Ref. 21]

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