Learning from the Soft Intelligence: Cephalopods as Indicators of Ocean Changes

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Cephalopods are exclusively marine invertebrates which have evolved into a unique and fascinating branch of marine biodiversity that has provided insight into many mysteries of the living world and our intrinsic connections to it. However, with ever-increasing human impact on the oceans, cephalopods are affected in many ways and can serve as indicator species to examine large-scale anthropogenic effects on the world's oceans. Several species have potential as a food resource, but this will depend on harvesting methods and sustainable practices. Cephalopods could serve as emblems representing marine biodiversity conservation, most notably for lesser-known and less charismatic marine invertebrates.

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INTRODUCTION

Anthropogenic effects on terrestrial systems tend to be fairly visible: many types of pollution on the land or in freshwater systems such as streams, lakes and rivers can be easily observed. For centuries, seas and oceans were considered so vast and so plentiful that few could imagine that mankind could exert enough influence on them. However, as the human population reaches beyond the 7 billion mark, evidence surfaces on a daily basis indicating that the ocean is not immune to pollution, nor is it a limitless resource. With mankind's increasing impact on the planet, it becomes ever clearer that we must carefully consider in what condition we intend to leave the environment for future generations (Simon 2011).

Cephalopods are an extraordinary class of animals: they are arguably the most advanced invertebrates known and they have gathered the interest of both scientists and the public throughout history and even more so today. They play combined roles of both predator and prey in their benthic or pelagic habitats. Their shorter lifespans and high growth rate allow for studies to assess the accumulation of pollutants in the short term and can be used to monitor pollutant accumulation rates in their more long-lived predators (which often consume large quantities of cephalopods) over the long term. Studies have been conducted to determine the effects of climate change, ocean acidification and chemical and noise pollution on cephalopods, which will provide useful information with which to compare their effects on both invertebrates and vertebrates. Based on estimates of the quantities of cephalopods consumed by predators, we may be able to determine how much may be harvested for human consumption in an effort to minimize damage to the natural ecological systems.

In the field of marine biodiversity conservation, the vast majority of the media and public attention is drawn to the charismatic megafauna of the seas, most notably whales, dolphins, penguins and sea turtles, etc. However, marine invertebrates comprise the vast majority of life in the oceans and yet nearly none of them garner as much public interest as other species. With increasing threats due to climate change and acidification, these invertebrates, many of which comprise the basis of the complex oceanic food webs, will be affected in ways which will subsequently alter consequences to the balance of marine life. As of now there is still pitiably little information available on the conservation status of cephalopods and other invertebrates; greater action must be taken in order to ensure their continued survival through greater education and awareness efforts.

Evolution and Anatomy

Cephalopods are a large class of invertebrates found in strictly saltwater environments- no cephalopods have been found in any freshwater systems, and only a few can tolerate brackish water (Hanlon and Messenger 1996). As a subdivision of the phylum Mollusca, they are related to the gastropods, which include all terrestrial and aquatic snails, as well as the bivalves such as clams, mussels and oysters. The Cephalopoda class is further divided into two subclasses: subclass Nautiloidea, which only contains the Nautilus family, and subclass Coleoidea, which is divided still further into multiple orders, families, genera and species (Hanlon and Messenger 1996). As of now, there are between 650 to 700 known living species of cephalopods globally, which seems relatively small compared to the estimated 10,500 or so different forms from the fossil record (P. R. Boyle 1983). Some genera may only contain a single species, whereas the genera *Octopus* and *Sepia* (cuttlefish) contain over one hundred species each. Coleoids can also be loosely categorized as either octopods (which have eight arms) or decapods (eight arms and two longer tentacles used for capturing prey). The undersides of the eight arms are covered in suckers along their full length whereas the two tentacles have suckers only on the club-shaped ends; these suckers are used for grasping prey and to gather tactile information from the environment (Boyle and Rodhouse 2005).

Paleontological evidence shows that cephalopods appeared in the fossil record approximately 450 million years ago, and were represented by nautiluses and ammonites, both of which secreted large protective spiral or cone-shaped shells. Most cephalopods today have either greatly reduced or internalized their shells or have lost their shells entirely in an evolutionary process that began about 100 million years ago (Boyle and Rodhouse 2005). The characteristic molluscan shell has been reduced to a thin internal ‘cuttlebone’ in cuttlefish and ‘gladius’ or ‘pen’ in squid, and has disappeared entirely in the octopus; only the nautilus retains a true spiral shell and has remained largely unchanged over evolutionary time. Those which lack a protective shell are left vulnerable to their many predators with their soft mantle (‘body’ containing internal organs) exposed; cephalopods as a result have developed a wide array of defensive adaptations to compensate for their lack of external armor. Other than shell remnants, the only hard structures in cephalopods are a chitinous beak around its mouth located at the base of its arms and a toothed ribbon appendage in the mouth called a radula, which is shared by their gastropod relatives; these are both used to tear prey into manageable pieces (Boyle and Rodhouse 2005).

The range of sizes in cephalopod species is startling; the largest currently known is the giant squid *Architeuthis dux*, which may reach mantle lengths of up to 5 meters, making them the largest invertebrates alive today and perhaps the largest that have ever lived (Hanlon and Messenger 1996). The streamlined torpedo shape of most squid allows for a quick getaway from slower predators using jet propulsion: water is forced forwards out of the mantle through a funnel in the direction of the arms (the anterior end), which propels the squid in the opposite direction (towards the posterior end). Squid also flap their muscular fins located on either side of the posterior end of the mantle to move either forwards or backwards. Cuttlefishes are not as pointed in shape as squid and move using jet propulsion or by undulating their fins which wrap around most of their mantle. Shallow-water octopuses generally lack fins and use jet propulsion or may “walk” along the seafloor using their arms (Hanlon and Messenger 1996). The lack of an internal skeleton allows cephalopods, most notably octopuses, to maneuver themselves into crevices and spaces smaller than their full bodies; an octopus can squeeze its way into nearly any opening larger than the diameter of its chitinous beak (Williams 2010).

When startled by predators, a cephalopod may also spray out a cloud of ink, a fluid of almost pure melanin to provide crucial seconds to escape from the suddenly confused hunter (Boyle and Rodhouse 2005, 32-33). Certain cephalopods such as *Loligo opalescens* also release ink containing dopamine compounds, maybe to temporarily hamper the olfactory sense of their predators such as eels before jetting away (Hanlon and Messenger 1996, 25).

Jet propulsion escape and inking defense mechanisms are generally used when more passive camouflage methods (described in detail later) have failed to work.

Cephalopods circulate a nearly colorless blood which turns blue when oxygenated; the blue color results from hemocyanin, a copper-based compound which performs similar gas exchange functions to the iron-based hemoglobin of vertebrates (Gilbert, Adelman Jr. and Arnold 1990). This blood circulates through three hearts: one for each gill, and another for the rest of the body. As dissolved oxygen is found in far lower concentrations in water than in air, cephalopods tend to seek out areas of cooler water which contains higher DO (dissolved oxygen) concentrations than does warmer water (Williams 2010).

Cephalopods possess an incredibly well-developed camera-lens type eye strikingly similar to those of vertebrates. Although it had been previously thought improbable, modern genetics findings suggest that the last common ancestor between cephalopods and vertebrates very likely possessed the basic genes necessary to form such complex eyes in the future; these genes merely changed in certain ways over evolutionary time into the kinds of eyes found today. But it seems that cephalopods do not have the ability to see colors or different hues, according to physiological studies and behavioral experiments. However, their vision may be far more sensitive to different levels of brightness and intensity of light than our vision (Williams 2010). Study results have also suggested that cephalopods show sensitivity to polarized light and can distinguish between different planes of polarization (Hanlon and Messenger 1996).

Behavioral Ecology and Life Cycles

All cephalopods are carnivorous- they are usually active predators which catch and eat live prey. Cuttlefish mostly feed on shrimps, crabs and fishes, octopuses feed primarily on crustaceans, bivalves and gastropods, and squid prey mostly upon fishes, crustaceans and cephalopods. Behavioral studies in the field have shown cephalopods to have developed specialized hunting methods and strategies for capturing prey by either using crypsis (camouflage) or by actively pursuing prey (Hanlon and Messenger 1996). The decapods typically grab prey by extending their two longer tentacles, while the octopods often grab and entrap prey under the webbing of their arms. Octopuses also immobilize their prey further by biting through the shells of their crustacean and molluscan prey and injecting saliva containing enzymes which detach the flesh from the shell to enable easy feeding; some species such as the Australian blue-ringed octopus *Hapalochlaena maculosa* also secrete paralyzing toxins which can be fatal to humans (Boyle and Rodhouse 2005). Cannibalism has been observed in many but not all species (Hanlon and Messenger 1996).

The coleoid cephalopods have remarkably high growth rates; this is most likely due to their high feeding rate and to highly efficient conversion of food into somatic growth. In short, they are highly efficient at turning food directly into biomass with less being lost from energetic exertion (a low-grade form of energy such as heat). Squid tend to be the most active pelagic swimmers, whereas the more benthic cuttlefishes and octopuses do not venture as far out into open water. As a result, the cuttlefish and octopus are more efficient at converting food into somatic growth than their actively swimming squid relatives (Boyle and Rodhouse 2005, 338).

The unique composition of cephalopod skin layers allows for skin coloration changes and camouflage abilities that are unparalleled in the animal kingdom. This versatility is thanks to the multilayered dermal coloration system: the top layer is comprised of chromatophore organs, which are tiny elastic sacs containing longer-wavelength black, brown, orange, yellow and red pigment granules surrounded by muscle. Cephalopods have acute control of these muscles (they are under direct control of the brain) and can direct individual chromatophores to display certain colors or patterns. Beneath the pigmented chromatophores are different types of ‘reflecting cells,’ of which three have been identified. Iridophores reflect iridescent colors for which there are no pigments, such as pinks, yellows, blues, greens or silvers. Reflector cells have only been found in octopuses and these mostly reflect blues and greens. Leucophores are below the iridophores or reflector cells and mostly reflect white. *Sepia* and *Octopus* genera, which have higher densities of smaller chromatophores, can produce much more complex patterns for camouflage than squids such as *Loligo* spp. which have lower densities of large chromatophores. Cephalopods can apply this pigmentation or color reflecting ability to effectively blend into their surroundings in order to hunt prey or to avoid visual detection by predators (Hanlon and Messenger 1996).

In deep-sea cephalopod species, patterning becomes less and less visible as the amount of light penetrating the depths decreases. However, deep-sea cephalopods, along with deep-sea teleost fishes and crustaceans can produce bioluminescence using light organs called photophores. Many use lights for counter-illumination, in which the undersides shine a light of a very similar wavelength and brightness of the water above them to mask themselves from predators lurking below them. Flashing lights at different frequencies may also be a method of communication, but much on this topic has yet to be understood (Hanlon and Messenger 1996).

Studies have been attempted in order to understand how cephalopods use coloration and pattern changes for communication. In Humboldt squid, for example, individuals can flash their entire body red or white in an almost strobe-light effect. Scientists have very few answers as to how this patterning is used and what signal it is meant to convey: whether it is directed towards prey, predators or conspecifics (National Geographic Society 2003). In addition to skin color and patterning, cephalopods may use body patterning and motions for visual communication (Hanlon and Messenger 1996).

Cuttlefishes and octopuses tend to remain solitary except when searching for mates, and at any other time may mildly tolerate conspecifics at best. Octopuses defend their shelters or dens but are generally not very territorial. Shoaling behavior can be seen in most squid species, but there do not appear to be any complex interactions within members of the group outside of mating times. They have been observed feeding as a group but no cooperative hunting has ever been seen (Hanlon and Messenger 1996).

Cephalopod sexes are separate, and mating behaviors are complex and vary highly by species. Males produce sperm packaged into spermatophores which are often transferred to the female via a modified arm called the hectocotylus. Fertilization is external in cuttlefishes and squids, and internal in octopods. Eggs may be deposited in communal masses by more social squids, or they may be hidden in crevices or other concealing areas.

Despite their incredible adaptations for survival, most cephalopod species are surprisingly short-lived; the average lifespan may be as short as one to two years. Many undergo a monocyclic semelparous reproduction: the sexually mature adults reproduce once or a few times during a period of their lives and die shortly thereafter. Physiological studies show that a great deal of energy is spent in reproductive organ development towards the end of their lives; the males often die soon after transferring sperm to one or several females, while females die soon after depositing eggs. Female octopuses brood and guard the eggs in a den until they hatch, keeping them well aerated and free of debris. All this time, the female does not eat. Once they have hatched, she directs them out of the den using jets of water from her funnel, and then later dies from starvation (Hanlon and Messenger 1996).

With their high growth rate, short lifespan and large quantities of offspring, many cephalopods are classified as r-selected organisms. This could have potential consequences for oceanic conditions as climate change, ocean acidification and other effects alter the species composition of the oceans (discussed later) (Wood 2011).

Many squid undergo daily vertical migrations: they rise to the ocean surface at night to feed on fishes which consume surface plankton, then dive back down to lower depths during the day. Humboldt or jumbo squid *Doscidicus gigas*, for example, frequent the deeper, colder (and more oxygenated) waters about 1300ft below the surface during the day, then swim up the water column to the surface at night to hunt for fish (National Geographic Society 2003). Many species of squid also migrate horizontally to different areas, either for reproductive purposes or to follow prey. Such migrations vary widely in distance and direction; some species may travel for hundreds or even thousands of kilometers. Octopods are generally sedentary, while cuttlefishes may migrate by following temperature cues. It is possible that migratory cephalopods may implement their sensitivity to polarized light to navigate using information from angles of sunlight (Hanlon and Messenger 1996). Much is still not understood about cephalopod migrations; it is hoped that attaching satellite tracking tags to live squids will provide more information about their migratory patterns. Neurobiologist William Gilly successfully used tags to demonstrate Humboldt squid migrations across the Gulf of California (National Geographic Society 2003).

Nautiluses: a Unique Exception

The chambered nautilus (4 species *Nautilus* spp.) differs in many respects to the other modern cephalopods. Nautiluses are the only living relatives of the once-large group of ectocochleate (outside shell) cephalopods that feature prominently in the fossil record. The nautilus cannot change its skin coloration for camouflage due to its lack of chromatophores, and it does not have an ink sac for defense against predators; therefore it maintains a spiral shell which serves as its primary defense from predators (Hanlon and Messenger 1996). The spiral shell's interior is divided into multiple chambers by walls. A small amount of gas travels through the chambers; this gas can be adjusted to different pressures to control the nautilus' buoyancy.

Unlike its complex camera-eyed relatives, it possesses a relatively primitive pinhole eye which produces comparatively poor vision (Hanlon and Messenger 1996). Nautiluses have a much longer lifespan, reaching maturity at about four to six years of age (P. R. Boyle 1983) and they are iteroparous, meaning that they breed several times after reaching maturity and may live up to 15 years or longer (Hanlon and Messenger 1996). Yet overall fecundity is low: females may only lay 10-20 eggs per breeding season (Boyle and Rodhouse 2005). In contrast to the modern coleoid species, the nautilus' strong shell probably reduces the need for a flight response; therefore the nautilus might not expend as much precious energy jetting away from predators. When exposed to low oxygen levels that would normally become a critical stressor to teleost fishes and coleoids, the nautilus can substantially reduce its metabolic rate to conserve the maximum amount of energy. Such low consumption of energy reserves means that nautiluses can get by with intermittent food from scavenging, which is perhaps one of the reasons they have survived for so long (Boyle and Rodhouse 2005).

Ecological Importance: Predators and Prey

Cephalopods maintain an important role as predators to many species of crustaceans, fishes and mollusks, including cephalopods. They are consumers which very likely aid in population control of these prey species, thereby mitigating the impacts of these prey species on the next lower trophic levels and contributing to nutrient cycling, both of which help to maintain a dynamic ecological equilibrium. Scientists can search cephalopod stomachs for tiny calcium carbonate structures used for balance called statoliths in cephalopods and otoliths in fishes to determine both age and species of their prey (Williams 2010). Understanding what cephalopod species eat will provide better understanding of their importance within a healthy ecosystem. When they first appeared in the Cambrian, cephalopods were most likely the top predators of the ancient oceans. Over evolutionary time, cartilaginous and bony fishes, reptiles and other new species appeared and became cephalopod predators, setting the evolutionary stage for the fishes, birds and marine mammals which prey upon them today (Clarke 1996).

Information on cephalopods as prey can be studied by examining the stomach contents of their predators. In sperm whales, stomach content studies show that they consume very large amounts of squid: large males may consume as many as 350 Humboldt squid (which can grow up to 6ft. long) per day (National Geographic Society 2009). Cephalopods' hard chitinous beaks are difficult to digest and can be found in stomach content examinations even after the soft flesh has been digested into an unrecognizable form. Specialists can identify individual species from beaks procured from a predator's stomach by comparing distinct characteristics such as size, shape, thickness, proportions and geographic source of the samples (Clarke 1986).

Based on new studies which examine the carbon and nitrogen isotope composition of beak specimens, one can also determine the approximate age and trophic level of certain cephalopod species. The results show that as cephalopods grow from juvenile to adult stage, they take on the role of higher predators on higher trophic levels. Such data could also help to better understand the trophic levels cephalopod species occupy within their respective marine communities and to identify which are key species in their ecosystems (Cherel and Hobson 2005).

Human Importance

Over a billion people worldwide depend on fishes as their primary source of protein, and over 16% of all protein consumed by humans comes from marine sources. But in order to keep up with the growing population, global fish catch would have to increase to 140 MMT (million metric tons) or more by 2025, which is far beyond the theoretically sustainable range of 69 to 96 MMT (Helfman 2007). As demand grows for high-quality protein sources to feed the world, more time, effort and investment have gone into cephalopod fishery harvests. Between 1990 and

1999, the global annual cephalopod catch increased from 2.4 to 3.4 million metric tons per year (Boyle and Rodhouse 2005, 278).

Not many individuals outside of the fields of neuroscience and biology are aware of the importance of cephalopods in the major discoveries of the functioning of neurons. In fact, cephalopods have the most advanced nervous system to be found in invertebrates, and these nerve fibers are very similar to our own. Atlantic squids *Loligo pealei* and *L. forbesi* have particularly long and thick axons (nerve fibers) which have made it possible to study the function of our own smaller neurons which are difficult to study without powerful microscopes (Gilbert, Adelman Jr. and Arnold 1990).

In addition, cephalopod ink has been used for writing and the cuttlebone from cuttlefish is sold in the pet trade as a source of calcium for pet birds (Williams 2010). Nautilus shells are also prized for their ornamental value (discussed in greater detail later).

The “Soft Intelligence”

In comparison to gastropods and bivalves, cephalopods are highly cephalized mollusks with a well-developed and comparatively enormous brain for invertebrates: their brain-size to body ratio actually is within the range of many vertebrates. A large part of their brains are dedicated to visual learning, while the octopus also has another portion of the brain for touch learning that is much larger than in squids. Many observations in the wild support that cephalopods use thinking strategies to avoid predation and to capture prey. In the case of coloration and body patterning, the brain processes visual information in order to send commands to the chromatophores and other cells. Octopuses also show spatial learning for finding their dens. Experimental studies show that cephalopods can learn from experiences and have both short-term and long-term memory (Hanlon and Messenger 1996).

In aquariums worldwide, octopuses on display are given enrichment puzzles and toys with food rewards locked inside. But it can be very difficult to design an appropriate puzzle for them due to our own paradigms on how information is processed, not to mention the limitations of our own anatomy (we cannot squeeze through small openings the same way an octopus can!). Perhaps our limitations in understanding the intelligence of cephalopods and other species are caused by a lack of creativity in our own thinking and intelligence. Understanding how cephalopods think may open up insights into how fishes and other invertebrates think, as well as provide information on how humans think in comparison with other animals (Williams 2010).

ENVIRONMENTAL CHANGES AND ANTHROPOGENIC EFFECTS ON CEPHALOPODS

Chemical Pollution

Toxic compounds such as mercury or heavy metals are generally present in minute amounts in marine ecosystems; human activities from mining and coal burning have increased their concentrations in ecosytems. Such compounds, as well as newer petroleum compounds such as PCBs and BPA may be taken up into primary producers such as oceanic phytoplankton in small amounts. Primary consumers consume many producers, thereby accumulating the toxic compounds to higher concentrations in their bodies. At each higher trophic level, the concentration of the toxin increases, perhaps up to dangerous levels in the top predators. This phenomenon is commonly known as bioaccumulation (Helfman 2007). Toxins may accumulate in cephalopods which consume contaminated fishes, crustaceans and mollusks; cephalopod predators in turn could potentially accumulate these toxins in harmful amounts, especially large predators such as sperm whales which consume vast quantities of cephalopods (discussed later).

Noise Pollution

Low-frequency sounds from shipping, offshore construction and resource exploitation have been known to harm fishes and cetaceans such as whales and dolphins. Such exposure to intense low-frequency sounds in the long term could alter the distribution, behavior and physical health of marine organisms. Still very little is known about the extent of chronic exposure and its effects on marine biodiversity, particularly on species known to be endangered.

New research has shown that cephalopods suffer from their own array of unique damages from low-frequency sounds. Cephalopods have statocysts- structures lined with sensory hair cells- inside the cephalic cartilage region. Statocysts are analogous to the vestibular system of vertebrates, which help the animal to maintain balance and to sense its orientation. These statocysts may also aid cephalopods in sensing low-frequency sounds. One pioneer study conducted a series of experiments exposing cephalopods to various levels and lengths of time of low-frequency sound, and examined the sensory hair cells under microscopes. Cephalopods which had been exposed to long periods of high-intensity low-frequency sounds showed damaged and destroyed hair cells and nerve fibers and other lesions, meaning that invertebrates can also be harmed in similar ways as previously-studied vertebrates. Such findings suggest that oceanic noise pollution should be carefully monitored to avoid large-scale ecological effects (Andre, et al. 2011).

Climate Change: Ocean Temperature and Migratory Patterns

Anthropogenic carbon emissions due to extensive combustion of fossil fuels have considerably altered the carbon dioxide concentration of Earth's atmosphere. Atmospheric CO_2 levels have increased by almost 40%, from 280 ppmv (parts per million volume) to nearly 384 ppmv by 2007 over the past 250 years (Doney, et al. 2009). As of today, this concentration has increased further to 388.92 ppm as recorded by Scripps Institution of Oceanography's Mauna Loa Observatory (McGee 2011).

However, the oceans act as buffers which absorb up to a third of total emissions, thereby mitigating its direct effects on the atmosphere. Without ocean uptake, atmospheric CO_2 concentrations today would reach levels higher than 450 ppmv, which would have even more severe effects on the climate (Doney, et al. 2009).

But the net atmospheric CO_2 levels even when alleviated by oceanic uptake have still had considerable effects on both terrestrial and marine systems. Today's concentrations are higher than at any point in the past 800,000 years of Earth's history (Doney, et al. 2009). Additional CO_2 exacerbates the enhanced greenhouse effect on the planet, which may lead to an average 3℃ warming effect on the Earth's surface by the end of the century.

Regional climatic patterns have shown signs of warming or cooling, which has altered species distributions as temperature-sensitive populations move to more suitable habitats if they are able to move. Fishes and plankton are among those that have been observed moving to new geographical locations, mostly in response to rising temperatures (Zeidberg and Robinson 2007).

Such warming trends over the decades are evident in the changes in phenological patterns in plants and animals when records from a century ago are compared with today's observations. Data show that terrestrial plants flower earlier and animals migrate and breed earlier in the year in response to longer and earlier warmer temperatures.

In a similar fashion, squid have been observed altering seasonal migration behaviors as a result of climate variability. A study observed veined squid *Loligo forbesi*, a commonly harvested squid in the English Channel, and compared the timing of their peak abundance in each year with the bottom temperature. *L.forbesi* completes seasonal migrations, moving from hatching grounds in the western English Channel eastwards by May where they undergo rapid growth and development, migrating back to western waters to spawn and die by December-January. After extensive scientific trawling studies, data showed that annual peak abundance along the eastern English Channel was significantly earlier in the year when the sea was warmer in preceding years. This fluctuation appears to have strong correlation to the North Atlantic Oscillation (NAO): early peaks occurred in years when the NAO was in its positive phase (warmer English Channel waters) and later peaks in negative-phase NAO years (cooler Channel waters). Such data have broader implications: the studies showed the intricate connections between water temperatures and migratory patterns in squid. As climate change alters the fluctuations, it could dramatically change the migratory timing of cephalopods (Sims, et al. 2001).

Though specialist species may be forced out of original ranges by warmer temperatures, this could conversely allow generalist species to expand their ranges. Humboldt squid *Doscidicus gigas* frequents the warm Equatorial waters of the Eastern Pacific, and is found in abundance along the coasts of subtropical North and South America. Warmer oceanic fluctuations during El Niño periods brought about Humboldt sightings off central California from 1997 to 2000. As ocean temperatures trend upwards, Humboldt squid have become a common sight in California waters (Zeidberg and Robinson 2007) and even as far north as coastal Alaska (Williams 2010). This may be due to climate-related shifts in the ranges of their fish prey, many of which are also harvested commercially (Zeidberg and Robinson 2007). As opportunistic predators, Humboldt squid have been compared to coyotes, as possibly both are capable of expanding their ranges in areas disturbed by human activities (Williams 2010). Yet as mentioned before, jumbo squid still must have access to cooler, oxygen-rich waters during the day. But as a result of atmospheric warming, average ocean temperature has increased down to 3000m deep, since the oceans have been absorbing about 80% of the heat added to the climate system. Higher temperatures decrease the oxygen affinity of hemocyanin in cephalopods' blood, which could put cephalopods with high metabolic rates at greater risk of asphyxiation (Guerra, et al. 2011).

Ocean Acidification- The Additional CO_2 Concern

As our oceans continue to absorb atmospheric carbon dioxide emissions, they experience dramatic changes in their overall chemistry, which in turn will have profound effects on marine organisms, particularly marine calcifiers- those which form calcium carbonate shells.

As CO_2 concentration in the atmosphere increases, so does the uptake of CO_2 at the ocean's surface, thus reacting with water to form carbonic acid (H_2CO_3). This weakly-ionized acid causes a decrease in oceanic pH, leading to acidification. Oceanic surface pH has already decreased since preindustrial times from 8.21 to 8.10 (Doney, et al. 2009). If emissions continue on their expected trajectory with no alterations, atmospheric concentrations could reach higher than 500 parts per million (ppm) by mid-century and could soar to 730- 1,020 ppm by the end of the century. Proportionately, this would lead to a decline of 0.3-0.4 pH units compared with today's levels (Munday, et al. 2010).

In conjunction with a decline in pH, the oceanic concentration of carbonate ion (CO_3^{2-}) decreases, leading to reduced calcium carbonate availability in seawater. Many marine organisms form shells and skeletons containing calcium carbonate in the form of aragonite or calcite, therefore a reduction in seawater's calcium carbonate saturation will presumably make the formation of a shell or skeleton more difficult (Gutowska, Portner and Melzner 2008).

As mollusks with shells or shell remnants containing calcium carbonate, cephalopods could be at risk in an ocean with a decreasing pH value. However, its effects may not be as fully predictable as once thought. Studies have shown that corals, echinoderms and bivalves reduce their calcification rates in response to elevated oceanic pCO_2 (carbon dioxide partial pressure). These organisms are also known for their low activity levels and low metabolic rates. But different results appeared when active, high metabolic rate cuttlefish *Sepia offcinalis* were raised in seawater with high pCO_2: their growth rate and metabolism remained the same as in those that were raised under normal conditions, and the experimental group was able to *increase* calcium carbonate accumulation to their cuttlebones, even when raised in seawater containing about 6000 ppm of CO_2. This could mean that some cephalopods may have a mechanism to cope with long-term hypercapnia (high pCO_2), perhaps giving them an advantage and the potential to increase in abundance if acidification trends continue (Gutowska, Portner and Melzner 2008). But maybe not all cephalopods may be able to maintain their metabolic rate, as oxygen affinity to hemocyanin also decreases with lower pH (Guerra, et al. 2011). The shelled nautiluses may respond differently as well; more studies must be conducted to better assess the effects of ocean acidification on the ectocochleate cephalopods. Altered pCO_2 levels could cause changes to other aspects of marine chemistry, such as the way potentially toxic metals accumulate in cephalopod eggs and larvae (Lacoue-Labarthe, et al. 2011).

In addition, cephalopods may be indirectly harmed by acidification if not directly: lower pH has been shown to inhibit normal growth and development of bivalves and crustaceans which will have increased difficulty forming their protective shells (Doney, et al. 2009). Young fishes also show altered behavior and a lower survival rate when exposed to seawater with increased parts per million of CO_2, thereby reducing the recruitment success of subsequent generations

(Munday, et al. 2010). Perhaps the cephalopods themselves may be able to withstand oceanic changes, but whether their prey will be able to adapt or not remains uncertain.

The Future of Cephalopod Fisheries and Harvesting Concerns

Should cephalopod stocks be managed in the same ways as are finfish stocks? Before this question can be answered, one must examine critically how fisheries stocks have been managed so far. Unfortunately, commercial overfishing has often resulted in collapsed stocks from insufficient recruitment, loss of genetic diversity within the overfished species and habitat destruction, especially from heavy trawling equipment which can severely damage coral reefs and disrupt sediments in benthic habitats. Another harmful result of unsustainable fishing is the large amount of bycatch: non-target species such as marine mammals and sea turtles may become entangled in the massive nets and die of asphyxiation (Helfman 2007).

In the decade from 1990 to 2000, cephalopod harvest increased by a substantial 42% as opposed to an increase of below 9% in total fishery catch. Many believe this to be a sign of a shift in fishing efforts as traditionally-fished species become harder to find and no longer abundant enough for commercial fishing efforts. This phenomenon has been termed 'fishing down the food web:' as traditional species are virtually fished out of existence (become commercially extinct), commercial fishing practices move on to the next available alternative (Boyle and Rodhouse 2005, 279). As a result, cephalopod numbers may increase due to reduced predation from fishes or that as ecologically opportunistic species such as the Humboldt squid (*Doscidicus gigas*), they could expand their ranges to fill ecological niches left vacant as a result of overexploitation.

Estimates indicate that there may be a great deal of cephalopod harvesting potential based on the sheer quantity consumed by their predators: whales are thought to consume over 320 million metric tons (MMT) of squid annually. Based on this estimate of cephalopod biomass, it has been extrapolated that 100 to 300 MMT per year could be harvested for human consumption, while some estimates say that it could be as high as 500 MMT per year (Boyle and Rodhouse 2005). These extrapolations suggest that cephalopod harvesting could increase by at least two orders of magnitude compared to today's harvests as discussed earlier. However, estimates of cephalopod populations are risky: open-water squid in particular are very challenging to quantify and the number of individuals can vary widely from year to year, likely more so than finfish.

Perhaps the most challenging component of comparison with teleost fisheries is the short lifespan of most cephalopods. Instead of a population consisting of cohorts of various year-classes as in bony fishes, r-selected cephalopod populations consist almost entirely of individuals of the same age: The following year's cephalopod catch depends entirely on the recruitment of offspring hatched from the previous generation the year or so before. Combined with climate variability and other factors which vary from year to year, this makes speculation of harvest abundance potential very difficult to predict (Boyle and Rodhouse 2005).

The chambered nautilus has been prized for centuries for the ornamental value of its beautiful cream-colored shell with orange-to-brown markings. The shell's shape represents Nature's repeating spiral pattern, mirrored in hurricanes and galaxies. When bisected, it reveals a pearly opalescent inner coating partitioned into ever-larger chambers as it proceeds from the center outwards in mathematical continuity.

But this fascination and love for the nautilus may ultimately lead to its doom if demand grows unchecked. As demand grows for nautilus shells for jewelry and decoration, harvesting in the South Pacific by low-income fishermen goes unregulated; this poses unique problems for the slow-growing nautilus population. Scientists have discussed potentially adding the nautilus as an endangered species, but are uncertain just how many nautiluses currently live in the Southeast Asian region spanning from the Philippines out to American Samoa. A census is currently underway to assess how much these cephalopods are under threat of extinction; if so their harvest may be regulated under the Convention on International Trade in Endangered Species (CITES) to ensure sustainability (Broad 2011).

Over-collection of cephalopod species for the aquarium trade may also be taking its toll on wild populations, which becomes all the more risky considering the continued lack of comparative population data. The Indonesian mimic octopus (*Thaumoctopus mimicus*), which is known for its feats of mimicry in the wild, is now difficult to find within its known range due to high demand from home aquarists. As no population studies have been conducted for this octopus (or for most other cephalopod species for that matter), there is no way of knowing how near this species is to extinction (Mather and Anderson 2007). Ironically, many of them die or are seriously harmed in the collection process (often through cyanide fishing) or in the shipping process, and most aquarists simply do not have the adequate resources to provide for its highly specialized needs (Caldwell and Shaw 2002).

MARINE BIODIVERSITY CONSERVATION SOLUTIONS

Conservation Measures

As of now, no cephalopod species have been declared threatened or endangered, but this is mostly due to lack of knowledge and data rather than the success of any conservation efforts (Mather and Anderson 2007). Information is surprisingly lacking concerning the conservation status of cephalopod species. The International Union for the Conservation of Nature (IUCN) has compiled an extensive database of species worldwide, with a particular focus on their conservation status. As of this November, the only classes listed under the phylum Mollusca are Bivalva and Gastropoda- absolutely no information on cephalopods is available (IUCN 2011). However, as reported in this year's April newsletter of the IUCN SSC Marine Conservation Sub-Committee, a small group of cephalopod specialists are currently preparing assessments for review and eventual listing (Allcock 2011). In fact, one of the largest factors as to why they have not been listed is that there is simply not enough information about species and population distributions and their overall ecology.

Rather than attempt species-based conservation and management efforts, perhaps the most effective way to protect cephalopods at risk would be to protect the areas in which they are found. Marine protected areas (MPAs) set aside large areas of coral reef or other ocean habitat for protection and to prevent their exploitation. The installation of marine protected areas (MPAs) is a true ecosystem-based conservation and management approach whose goal is to maintain and possibly improve the total biodiversity and productivity of an area. Ideally, adult individuals which matured within an MPA may disperse to colonize surrounding areas (the spillover effect) and larvae spawned within an MPA may travel out to outside areas as well (the recruitment effect) (Helfman 2007). This approach has been found to be successful in many cases in tropical areas for reef fishes and invertebrates and may be the best conservation measure that can be implemented to protect the more sedentary cephalopods such as cuttlefish and octopuses.

A New Emblem for Marine Conservation?

In order to garner public interest for biodiversity conservation, many of the leading conservation organizations have adopted particular species to serve as emblems for the cause. One of the most recognizable emblematic species is the panda featured on the World Wildlife

Fund's logo (World Wildlife Fund 2011). The WWF has been hugely successful in promoting awareness of species and habitat conservation, most notably for the charismatic megafauna such as large mammals. However, such organizations may possibly overlook the less charismatic, less well-known yet essential species in their awareness or education programs.

When it comes to species-centric conservation, the public most often takes an anthropocentric view towards which species are considered more worthy of conservation efforts. Indeed, much of what inspires conservation action by the public is the ability to relate to the species, to find common connections between the species of interest and themselves. Although 99% of all species on Earth today are invertebrates, they are not very well understood or valued by the general public (Mather and Anderson 2007). Many people tend to fear and dislike invertebrates, particularly arthropods such as insects and spiders or mollusks such as snails which are often considered pests.

As evidence increasingly reveals the complexity of cephalopods, ethical questions have arisen concerning their humane treatment, whether in experimental studies, harvesting for food or when considering species conservation. One of the most crucial ethical considerations is ensuring a species' continued survival in the wild, yet invertebrate conservation awareness is unfortunately lacking, even though more invertebrates have become extinct in the past two centuries than all mammals and birds combined. Traditional thought maintained that invertebrates were too low on the hierarchy of life- the 'scala naturae'- to possess any indication of intelligence or cognition. However, increased studies of invertebrate behavior, especially cephalopods, have begun to change the way people think of invertebrates and may inspire public awareness and support for invertebrate conservation (Mather and Anderson 2007).

Stories and legends about massive squids have pervaded human culture for centuries, adding to the mystique of cephalopods. Arguably the most infamous cephalopod to capture the imagination has been the giant squid *Architeuthis dux*. The only clues to its existence were the occasional carcasses which washed up onto beaches, until a team of scientists managed to lure a live giant squid close enough to capture the first photographs in history of a living specimen (Kubodera and Mori 2005). Preserved specimens can be found in museums worldwide and continue to draw in crowds of curious visitors. Such popularity has brought about the suggestion that the giant squid be used as an emblem to symbolize marine biodiversity conservation, particularly for invertebrates. As a cephalopod, *Architeuthis* is a good indicator for changes in ocean ecosytems which have become more vulnerable due to climate change, ocean acidification and other human activities (Guerra, et al. 2011).

Education as a Key Component towards Conservation

Aquariums and zoos around the nation and around the world put primary effort into promoting education and awareness to the public about the animals they have on display in order to inspire visitors to take steps to protect their wild counterparts and their habitats.

As an intern with the Education Department at the National Aquarium in Washington, DC, I had the incredible opportunity to participate in a series of seminars on improving climate change education and awareness to the public at this and other aquariums across the nation. My co-intern and I collaborated with National Aquarium staff and volunteers to compile a series of ongoing talks titled “Critter and Climate Chats.” These short yet engaging presentations for visitors highlight interesting facts about a species on display (like our giant Pacific octopus *Octopus dofleini* for example), describe the conservation challenges faced by this species, and conclude by describing individual actions a person can take to aid in their conservation.

Over the summer, I was proud to play an active role in contributing to the education of the general public about aquatic organisms and the need for both their conservation and the conservation of their ecosystems. I will continue to play this active role through continued volunteering at the National Aquarium, throughout my career and throughout my lifetime.

CONCLUSIONS

Since the dawn of civilization, mankind has interacted with the ocean. It is a world teeming with life that in some ways may seem alien to us, but our deep evolutionary origins all point to the sea as the cradle of life on our planet. Much of our resources, including food, pharmaceuticals and raw materials come from the oceans. The more information we gather about marine species such as cephalopods, the more questions arise concerning their roles and importance to marine ecosystems, and how they may be impacted by harvesting, climate change, acidification and pollution.

Marine science, including marine biology, continues to make scientific breakthroughs. Although the oceans have been a subject of awe, wonder and discovery throughout human history, only a tiny fraction of marine surface has been explored. Our planet would be a very different and far less hospitable one were it not for the oceans; therefore it is essential to learn all that we can, for human activities are causing ecological changes in the oceans before we can even understand how they are changing. Marine science remains a frontier for discovery, inspiring many such as myself to pursue study in marine biology and other fields. It is up to this generation to become inspired to protect the biodiversity of our oceans for the sake of future generations and for the sake of all life on Earth.

Images

Source: http://www.arkive.org/giant-cuttlefish/sepia-apama/image-G68573.html
The giant cuttlefish (*Sepia apama*) demonstrates its incredible camouflage ability: it uses visual information from its well-developed eyes to match the patterns of its surroundings by controlling the pigments of its chromatophores .

Source: http://www.arkive.org/common-octopus/octopus-vulgaris/image-A19368.html
The common octopus (*Octopus vulgaris*) shows its talent for camouflage (using chromatophores) and its ability to squeeze into small spaces in a coral reef.

Source: http://invertebrates.si.edu/giant_squid/Beak.html
Squid expert Clyde Roper from the Smithsonian Institution's National Museum of Natural History presents the beak of a giant squid (*Architeuthis dux*). Surrounding the chitinous beak are powerful muscles from the buccal mass; inside the mouth is the toothed ribbon called a radula which also helps to tear its prey into edible pieces.

Source: http://www.arkive.org/nautilus/nautilus-pompilius/image-G66652.html
The chambered nautilus (*Nautilus pompilius* in this case) is distinctly different from modern cephalopods, retaining more similarity to extinct species such as ammonites. Their shell is highly prized for jewelry and ornaments, which could place these slow-to-mature animals in danger of extinction.

Source: http://www.arkive.org/humboldt-squid/dosidicus-gigas/image-G76787.html
The Humboldt or jumbo squid (*Dosidicus gigas*) is a relatively large squid which has recently expanded its range along the western coast of the United States for uncertain reasons. This range expansion may be due to climate-related oceanic changes.

Source:
http://dsc.discovery.com/news/2006/12/22/giantsquid_ani_zoom0.html?category=animals&guid=20061222113000
This is one of the images captured by the Kubodera and Mori research trip, which was the first to photograph a live giant squid in the wild. This female measured over 20 feet long and was caught off the coast of Japan. Much is still unknown about the behavior or even the abundance of these mysterious squid.