Discoveries of the Census of Marine Life:
Making Ocean Life Count

Over the 10 year course of the recently completed Census of Marine Life, a global network of researchers in more than 80 nations has collaborated to improve our understanding of marine biodiversity – past, present, and future.

Providing insight into this remarkable project, this book explains the rationale behind the Census and highlights some of its most important and dramatic findings, illustrated with full-color photographs throughout. It explores how new technologies and partnerships have contributed to greater knowledge of marine life, from unknown species and habitats, to migration routes and distribution patterns, and to a better appreciation of how the oceans are changing. Looking to the future, it identifies what needs to be done to close the remaining gaps in our knowledge and provide information that will enable us to better manage resources, conserve diversity, reverse habitat losses, and respond to climate change.

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3 NSERC Canadian Healthy Oceans Network, a research collaboration of
4 65 marine scientists from coast to coast in Canada that continues to census
5 ocean life.
Discoveries of the Census of Marine Life:

Making Ocean Life Count

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Foreword

We went first to the moon

Life on Earth originated in the margins of the primordial ocean and for billions of years evolved in this aquatic milieu. Life originated on Earth because it has the Ocean: water in liquid state on its surface. Although curiosity has pushed humanity to search for life in outer space, we still know no other planet with life in the universe. One Planet, one Ocean.

Unquestionably, from a planetary perspective, the ocean is a thin layer of fluid that plays an essential role in making the planet livable. The ocean is to Earth thinner than the skin to an apple. However, to our human scale and resources, the oceans represent a vast tri-dimensional space, opaque to our vision and full of unknowns. In the 1960s, in the middle of the Cold War and the race for space exploration, a campaign called for conquest of “the inner frontier,” to mount a major research and technology effort to explore the ocean interior. As we all know now, we went first to the

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1 On average the radius of the planet is 6,371 kilometers, the ocean on average is 3,733 meters deep, i.e. a thickness of 0.058% or 6 ten-thousandths of the radius.
We haven’t extracted a single gram of food from the moon, but in the last 60 years we have extracted over 3,500 million tons of fish from the ocean and roughly half of our natural gas and oil come today from the ocean floor.

But what we always fail to understand, beyond these immediate and selfish uses, is that the ocean provides essential ecological services to all humanity, making life possible on our planet: the ocean is the ultimate global commons, something that belongs to all of us. One example: marine photosynthesis produces annually 36 billion tons of oxygen, estimated to equal 70% of the oxygen in the atmosphere. I cannot think of a more fundamental reason to assert that every form of life on Earth has a stake in the health of the ocean. Humanity, mastering the technological power to disrupt its equilibrium, is especially responsible for its health.

The ocean under the pressure of numbers...numbers of humans, that is

Many human uses of the ocean have secondary effects that adversely impact the stability of natural processes in the ocean. Alarming signs alert us that the integrity of several natural systems that provide basic ecological services to humanity is threatened. Evidence accumulates to
demonstrate that the management systems that we use do not suffice to guarantee the sustainability of living marine resources.

Destruction of critical coastal habitats is alarming, as human populations fill the shores. Destruction of deep-ocean habitats is significant due to the secondary effect of fish trawling. The frequency and size of dead zones increase due to the exhaustion of oxygen by the arrival of vast quantities of chemicals used by, or originating in, industry, agriculture, and animal husbandry, and transported by rivers into the ocean. Satellites and sailors detect massive accumulation of plastic in the central gyres of the Pacific Ocean.

Absorbing millions of tons of CO₂ every year – roughly one-third of total annual emissions – the ocean has already spared us from catastrophic climate change. But in doing so, its own intrinsic balances are altered: the ocean is becoming more acidic and has taken the largest fraction of the additional heat generated by anthropogenic greenhouse gases, something that might eventually alter the normal patterns of ocean circulation essential for keeping the absorbed CO₂ from reuniting with the atmosphere for long periods, buying us time for finding solutions to climate change.

We have an incomplete and piecemeal picture of what is happening to the ocean and an urgent need to generate the compelling evidence that
should force us to adopt corrective policies at the highest level possible. Too much is at stake to follow the path of least resistance. The book that you have in your hands is the first digest synthesizing a unique scientific program designed to move the boundary of the unknown in the ocean: The Census of Marine Life, catalyzed by support from the Alfred P. Sloan Foundation and composed of 17 different international projects that in 10 years mobilized more than 2,600 researchers in 500+ research expeditions, added several thousand new species to science (and counting), put together over 22 million records of individual ocean specimens, and produced thousands of contributions to the scientific literature.

Abnormal science

Normal science builds upon the many contributions that researchers make when setting for themselves a research goal that eventually results in a published paper. Each step tries to answer the immediate knowledge gap in a logical sequence of analysis of a single phenomenon. Apparently there is no a priori plan, but collectively these individual contributions build the edifice of science, and push back the boundary of the unknown. The Census of Marine Life is a different intellectual enterprise. Disregarding many objections from Mainstream Road, the leaders of the
initiative used a metaphor to rally the interest of the relevant scientific community: to conduct a *Census* of marine life, an impossible task *sensu strictu*. By choosing an extremely broad subject, the living ocean, and setting a research vector, or direction, to count and account for the living in the ocean, the founders were able to form a community of researchers with quite disparate research interests and objectives, to weave a delicate fabric of research topics that brought together the main ingredients of scientific discovery: deploying new technologies, poking through disciplinary boundaries, transporting knowledge produced in one field to another, attacking simultaneously the small and the large and the extremely large scales usually unavailable to single teams of scientists. Using as an epistemic Occam’s razor the distinction between the known, the unknown, and the unknowable, they collectively and systematically selected a limited number of bets to maximize results. This book demonstrates unreservedly their success.

**Around the living ocean in 10 chapters**

Modern scholastics divide the study of the ocean in the physical, chemical, and biological oceanographies; marine biology, concentrating more on the organisms themselves and currently flourishing thanks to genomic techniques; and marine geology and geophysics, plus all the engineering subsumed in the applied ocean sciences. What this scholastic
division misses is that the ocean itself is alive. I am not falling into a
mystic lapse suggesting a Spencerian superorganism. The discovery both
of the highly diverse chemosynthetic biological communities of
hydrothermal vents and deep-ocean seeps and of the rich and abundant
microbial life in the upper 100 meters of sedimentary ocean bottom are
new facts changing our collective perception of the ocean. Without
understanding life in the ocean we will never understand the complex
system that the ocean is. Life is immediate to chemical and biological
oceanography and geology. The ultimate equilibrium of climate on the
planet most likely will be biologically set. Following a long and venerable
tradition, the Census went out with new tools to study patterns within this
living ocean. This book reports back that this choice was extremely
fortunate and successful, turning up everywhere discoveries, as these
fascinating pages reveal.

I will not summarize here the content of each chapter of this digest. I
will idiosyncratically choose certain highlights.

Animals that are strong swimmers may move distances of hundreds or
even thousands of kilometers in pursuit of mates, food, suitable
temperatures, and oxygen that enhance their survival, growth, and
reproductive success. On the technology side, the Census developed new
electronic tags for organisms that were massively used. Within the
Tagging of Pacific Predators (TOPP) project some tags recorded physiological functions, most were capable of determining geographical position through GPS, and all transmitted data through satellite, allowing the tracking of animal movement across the ocean. This enabled the identification of “hot spots,” “cold spots,” “highways,” and “truckstops” of many different types of animals. These are ocean regions where they feed, reproduce, or correspond to preferred migration routes. This information allows us fascinating glimpses how animals, other than humans, use the marine environment. It provides unique and highly applicable information for the protection and management of the ocean.

Still on the technology side, within the Pacific Ocean Shelf Tracking (POST) project the development of large “curtains” of sensors enabled the precise counting of individual organisms while they massively migrate in the ocean. This is being used and applied to monitor salmon populations in the North Pacific and is already informing management decisions.

The Census benefited from the fast development of molecular biology and genomics in recent years, the precise reading and identification of genetic material in organisms. The “barcode of life” methodology broadly applied as part of the Census of Marine Zooplankton (CMarZ) project can rapidly reveal whether two organisms belong to the same species. A barcode of life is a short DNA sequence from a uniform locality on the
genome that can provide a true molecular ID card for each marine species.

This allows major steps forward in elucidating the presence of many
cryptic species in the ocean, by distinguishing species that superficially
resemble one another, and joining specimens that vary in appearance from
one region to the next. CMarZ has targeted potential biodiversity hot spots
throughout the world, including poorly known regions such as Southeast
Asia, the polar oceans, and the water column below 5,000 meters. Another
related molecular technique, pyrosequencing, was widely used by the
International Census of Marine Microbes (ICoMM) project, as they built a
completely new picture for marine microbial diversity and abundance, and
the role microbes play in the global ocean.

A single liter of seawater contains more than one billion microbes.2
Marine microbes account for perhaps half of the primary production that
fuels all life on Earth and they control the global cycling of nitrogen,
sulfur, iron, and manganese. Without microbes, life on Earth could not
exist.

The Arctic Ocean Diversity (ArcOD) Project and the Census of
Antarctic Marine Life (CAML) both participated in barcoding. Using

2 ICoMM estimates approximately 100,000,000,000,000,000,000,000,000,000,000,
(or 10^{29}) total bacteria in the global ocean and about 20,000 operational
taxonomic units (a proxy for species) in a typical liter of seawater.
similar techniques to those championed by CMarZ and ICoMM, polar microbiologists discovered 1,500 types of Arctic bacteria and 700 types of archaea. CAML has added over 11,000 barcode sequences for Antarctic species from their collections. The Census is working with MarBOL (Marine Barcode of Life) to compile a marine library and expects to have accumulated reference codes for 50,000 species by the end of 2010. Researchers active in the Census of Coral Reefs Ecosystems (CReefs) are working to apply variants of environmental genomics involving mass sequencing developed for microbes to assist in coral-reef taxonomy.

I cannot finalize this review without mentioning the History of Marine Animal Populations (HMAP) and the Future of Marine Populations (FMAP) projects, which both studied changing oceans. Employing a wide variety of historic, anthropological, and natural-science methods and techniques, HMAP made the most serious effort to date to reconstruct a vision of life in the ocean before massive human interference. HMAP has produced sobering baselines that should add depth and effectiveness to management decisions. FMAP has continued that timeline forward to produce new global views of diversity, distribution, and abundance that illustrate the current scope of human impact. These and all the other Census projects contribute data to the Ocean Biogeographic Information System (OBIS), the Census biodiversity data legacy.
To conclude I want to highlight the use that the Census made of innovative sampling techniques to access remote and inaccessible areas of Planet Ocean. The five Census projects looking specifically into the deep ocean, down the continental slopes, through vents and seeps, across the abyssal plains, and up over seamounts and the Mid-Atlantic Ridge, used new submersible tools, towed cameras, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and manned submersibles.

Da capo a fine

In a fortunate coincidence, Chapter 10: “Planet Ocean beyond 2010,” brings us full circle to the question of why humanity went first to the moon: “Satellites continuously orbit the Earth, collecting imagery for myriad applications. Autonomous underwater vehicles (AUVs) may soon move across the seafloor like underwater satellites. AUVs today run well-defined, pre-programed missions. (...) The next generation AUVs may visit underwater docking stations to recharge their batteries and download their data.” This extremely powerful vision is also a declared need of the international community. The World Summit on Sustainable Development in 2002 decided to keep the oceans under permanent review via global and integrated assessments of the state of ocean processes. This initiative for a world ocean assessment is the most comprehensive yet undertaken by the
United Nations system to improve ocean governance. Implementing it will make full use of the baseline 2000–10 established by the Census. Maintaining it through time will require a permanent program of observations of the living oceans that complements what we now have for the physics of the ocean and climate. As this digest abundantly demonstrates, the Census of Marine Life did its part.

Patricio A. Bernal

Executive Secretary (1998–2009)

Intergovernmental Oceanographic Commission

Paris, March 2010
Part I

The unknown: why a Census?
Chapter 1

Planet Ocean

1. We are a species that breathes air rather than water, which biases our view of the watery Planet Earth. We might better call a globe with 71% water cover and more than 99% of its living biosphere in marine waters Planet Ocean, as noted years ago by the writer Arthur C. Clarke (Figure 1.1). We are far less familiar with the ocean than the land. Even for scientists working in the ocean for all of their lives there are surprises. Shocked to see a recent photograph of a clam named Pholadomya candida that was thought to have been extinct since the late 1800s, a Colombian scientist spent many days diving and searching where the photograph had been taken. Just before his scuba tank ran dry one day, he found a living specimen a little deeper and in colder water than expected, rescuing it, at least temporarily, from the list of extinct species. Deep-water samples my research team recently collected from Eastern Canada were examined by a world authority on marine worms, who was surprised that half of the species had never been named. This novelty appears to be the norm for many deep-water environments, where as much as 85% of the species in a sample can be new to science.
These anecdotes illustrate how little we know about Planet Ocean and what lives in it. The ocean is changing, and it is changing before we have really appreciated all that it now contains. What lives in the ocean? Where do they live? How many are there? In three words, what is their diversity, distribution, and abundance? We are further from answering these basic questions than even most scientists realize.

To answer these three major questions, marine experts from around the world banded together in the year 2000 in an international initiative called the Census of Marine Life. In the decade of discovery that followed, as this book summarizes, the Census and others focused new “binoculars” of technology to look into the ocean and propelled forward the understanding of diversity, distribution, and abundance of marine life. Through the chapters that follow, we will visit the different areas of the ocean and use these new “binoculars” to see and understand single-celled microbes and whales, and everything in between, in ways not possible only a decade ago. In short, Planet Ocean is coming into focus, and is becoming more transparent.

The array of marine life and how they live varies immensely. The size of marine organisms ranges a hundred million million million million fold, from drifting bacteria through blue whales. From the smallest to the largest
organisms, from the shortest to the longest lived, from the slowest to the
fastest, and from the drab to the flamboyant, living organisms have
developed an amazing range of strategies to survive. Some species, such
as bacteria, may only live for hours, but they can also replicate in that time
and produce multiple generations in the time it takes us to get a good
night’s sleep. At the other extreme, as impressive as specimens of 200-
year-old rockfish and 400-year-old clams may be, these long-lived species
pale in comparison with deep-water corals that can live in excess of 4,000
years (Table 1.1). Imagine that when this coral first settled to begin life,
Egyptian and Minoan cultures were flourishing, and Tutankhamun had not
yet begun his reign. Indeed, this coral would have been over 1,000 years
old when Buddha and Aristotle were born!

Some species are prolific and others are not. Many long-lived species
produce few offspring after many years, in contrast to many species that
produce millions of offspring, sometimes only months after they
themselves were born. Mobility also varies. Corals are affixed to a single
seafloor location, but other species move quickly and far. Sailfish can
rocket through the water at 110 kilometers per hour. Atlantic bluefin tuna
can move quickly, too, but take their transatlantic migrations of 5,800
kilometers at a more leisurely single kilometer per hour. Sooty
shearwaters complete their 64,000 kilometer roundtrip migrations at 40 kilometers per hour, faster than most of us can move as we commute to work! The real marathon swimmers are humpback whales that complete 8,400 kilometer migrations, and Pacific tuna that make triple crossings of the Pacific.

Tricks of survival are many. Whereas species such as flounder can adjust their color to blend in with the environment and make themselves invisible to predators, nudibranch sea slugs alert predators that they are poisonous through bright colors. The diversity of life, its size, and its longevity reflect a wide range of adaptations evolved through time to survive in Planet Ocean (Figure 1.2).

Why a Census?

Beginning with environmentalist Rachel Carson’s *The Sea Around Us* and continued by Jacques Cousteau’s films, interest in oceans grew through the 1970s. Books and television brought the beauty of the ocean into living rooms of homes around the world. The complexity of the *neritic* (coastal) environment and the *size* and remoteness of the *pelagic* (offshore) environment awed people. *Environment* is the sum total of physical, chemical, and biotic factors (such as ocean currents, nutrients,
prey) that act upon an organism or an ecological community and ultimately determine its success and failure. The environments that awed people supported fisheries that in turn supported many economies around the world. But by the 1960s and 1970s, some fisheries were obviously declining, and as the environmental movement took off, interest in living organisms was rising. Scientists began to appreciate the array of life in the ocean, debated the patterns and causes of diversity in coral reefs, and fueled interest in the myriad species that had been discovered in the ocean.

Much of this interest was confined to a few specialists, and interest in diversity and the underlying taxonomy declined by the early 1990s. Soon after that, the rise of conservation biology, projections of millions of unknown species in tropical rainforests, and E.O. Wilson’s and J.F. (Fred) Grassle’s writings about diversity on land and sea revived interest in species diversity.

Wilson helped to bring to the public the term biodiversity for the variability in genes, species, and ecosystems of a region, evolving it from the more general term diversity. Although some scientists continued to study biodiversity patterns in coastal areas and the deep sea, and the processes that contributed to those patterns, major funding and effort to study marine biodiversity did not materialize.
Meanwhile, the collapse of major fisheries once thought to be inexhaustible alarmed the public. Though explaining year-to-year variation in abundance had vexed biologists for a century, and although many fisheries had waxed and waned over the years, the global scale and gravity of fisheries collapse hit home in the 1990s. The effects of removing the top predators from whales to sharks to fishes cascaded onto other species. The cascade of effects from the ocean surface to the seafloor provided evidence of unintended consequences of fishing on ocean productivity. Effects on biodiversity extend far back in time. These concerns shifted fisheries managers away from focusing on single species to viewing entire ecosystems. They recognized the negative impacts of fishing on habitats and food webs.

An additional wrinkle was the new idea of ecosystem services. This concept refers to the key services from living organisms that benefit all life on Earth and, in many cases, benefit humans directly. In the ocean, these services include breakdown of sewage and other waste, nutrient cycling, shoreline stabilization, and provision of food and oils. Scientists argued that because biodiversity made ecosystems healthy, changes in biodiversity could diminish ecosystem services. This concern offered a practical application to move biodiversity research beyond a descriptive exercise to finding how oceans actually work, and then apply those findings to management. The role of biodiversity in ecosystem services
matters because major changes have taken place and continue to occur in
the ocean. Human production of pollutants and climate-change gases, plus
fishing in the deep ocean caused many of the changes. Will changing
biodiversity in the ocean influence ocean productivity and other
ecosystem services?

Ocean biodiversity

During the late 1990s, some experts estimated that less than 5% of the
biodiversity in the ocean had been described. Indeed, some estimated less
than 1%. Even comparatively well-known seas, such as the shallow waters
of northern Europe and the northeastern United States, continue to yield
new discoveries of species and surprises about the life they contain. Much
of the ocean remains unsampled. Biological data for the deep ocean
beyond 200 meters depth exist for only a few square kilometers of the 300
million square kilometers of Planet Ocean. Much of the biodiversity on
coral reefs remains to be sampled. And we are just now starting to learn
about the diversity of microbes, whose unknown biodiversity could
explode our estimates of the number of marine species.

During the last few decades, our understanding of life on Earth has
broadened from one of life divided into five all-encompassing groupings
to a new recognition of three domains. The first domain, the Eukarya or
eukaryotes, encompasses the animals, plants, fungi, and microbial protists, (single-celled, simple organisms such as amoebas), all of which have nuclei and other specialized organelles within their cells. The other two domains, the Bacteria and bacteria-like, but different, Archaea, comprise the prokaryotes that lack most of these organelles. The broadened view of the diversity of life on Earth includes understanding how species have evolved. Molecular tools that tell how groups of organisms are related in an evolutionary context made this new view possible. Our view of life on Earth has been reorganized.

Counting all the fish in the sea

In 1995, the United States National Academy of Sciences emphasized the need to fill major gaps in understanding ocean life. The ensuing inaction discouraged Fred Grassle, a leading voice on marine biodiversity. One summer afternoon in 1996 he walked into the office of Jesse Ausubel, a program officer with the Alfred P. Sloan Foundation, and lamented the discouraging problem. They explored what to do about it. To some extent, a coincidence of geography – strong ties to Woods Hole Oceanographic Institution – brought Grassle and Ausubel to the same small town and marine science Mecca, where I wrote these chapters as a seasonal guest. As Rachel Carson noted almost 50 years ago, “Woods Hole is a wonderful place to come for research. Biologists come from all over. If you want to
talk to them, you just come here in the summer instead of traveling all
around the country to find them in winter.”

At the time, the Sloan Foundation was supporting the first Digital Sky
Survey to map the one hundred million objects in the sky. Grassle’s
concern intrigued Ausubel, and after further discussions, they developed
the idea of “mapping” life in the ocean. Some weeks later, Ausubel
strolled with one of his Sloan colleagues towards Aquinnah on the island
of Martha’s Vineyard and, while inhaling salt air and scanning the ocean
edge, announced, “We’ve helped astronomers count all the stars in the
sky; let’s help marine scientists count all the fish in the sea.”

Appropriately, Aquinnah (formerly Gay Head) stood at the beginning of a
sampling line established by Howard Sanders, one of the fathers of deep-
sea biology, in the 1960s. The line ran all the way to Bermuda and its
study changed our understanding of marine biodiversity. Grassle’s passion
for marine diversity, and especially the *invertebrates* or animals without
backbones, ensured that “fish in the sea” would not be taken literally, and
his dream of a global program in marine biodiversity began to become a
reality.

During the next three years, marine experts from around the world
gathered to talk, identify research gaps, and formulate a strategy to
understand life in the ocean. They came from wealthy countries and poor
ones, from polar research labs and the tropics, and with interests from whales to bacteria. They met in marine centers around the United States and United Kingdom, and in Greece and Thailand. A plan emerged to undertake an unprecedented 10 year census of the world’s marine life in an international program called the Census of Marine Life. The overarching goal of the Census would be to understand the diversity, distribution, and abundance of marine organisms across all ocean realms from the shoreline to the ocean abyss, and to consider their past, present, and future. The task was formidable, because the concept was global in scope and aimed to sample the vast oceans and their diversity of life.

Unlike the censuses that count the single species of humans with fixed addresses in single nations, this Census would consider all species and ocean habitats. Most of the ocean has never been sampled or seen because much of it is thousands of kilometers from land and several kilometers deep. And some of the most species-rich waters of the ocean are near developing countries with little funding and infrastructure for research and exploration.

The ocean constantly changes as the sun rises and sets, as wind blows and seasons change, and as such phenomena as El Niño wax and wane. Many waters straddle national and international boundaries and organisms move through entire ocean basins in a matter of weeks and months. Until the Census began, marine biology lacked coordination in biodiversity
research, particularly internationally. Scientists had worked together on
fisheries problems in groups such as the International Council for the
Exploration of the Sea, but the groups focused largely on single species
targeted by fisheries. Uncoordinated efforts to study biodiversity produced
findings, but could not capture the broad variability in space and time of
marine diversity, distribution, and abundance in the global ocean as the
planned Census hoped to do.

Bringing together experts from around the world facilitated
coordination. The gatherings introduced individuals from developing
nations with limited equipment, ships, and knowledge of sampling, to
experts from developed countries with more scientists, resources, and
links to multinational programs. The gathered scientists discussed
objectives, oceanographic cruises, sampling, and analytical methodologies
so they could work together to tackle big questions that no individual or
nation could hope to answer alone.

Indeed, the crowning achievement of the Census may not be the
thousands of scientific papers it has catalyzed and their many findings.
Rather the crown may be exciting and unifying global researchers toward
the common objective of understanding life in the ocean and managing
ocean resources effectively.
Although programs such as the Human Genome Project or the World Ocean Circulation Experiment (WOCE) have tackled big questions through international collaboration, they have typically addressed a single big question with one set of techniques. The Census has instead used tools, from rubber boots to robots and molecular biology to satellites to study the diversity, distribution, and abundance of microbes to whales. From fishermen concerned about declining catches to conservationists worried about extinctions and habitat loss, all these groups stand to benefit from coordinated studies of the oceans and communication of scientific findings. The legacy of cooperation and collaboration represents a new way of doing integrative science at a truly global scale that will live long after the formal Census ends. From the seafood aisle at the supermarket to tourists snorkeling the reefs outside their beachfront hotel, the legacy will provide enduring benefits.

The Census of Marine Life

The complexity and scale of the Census attracted thousands of experts from more than 80 nations (Figure 1.3), who rallied around understanding marine biodiversity, distribution, and abundance in the past, present, and future. They organized into 17 interlinked projects (Table 1.2 and summarized on the inside back cover) that divided up the scientific tasks to focus on contrasting ocean habitats, groups of organisms, regions, and
how the ocean has changed in the past and will change in the future (Figure 1.4). They then worked together to synthesize the many findings into an understanding of the global ocean. In the largest study ever undertaken of marine life, this team developed new technologies and partnerships to generate knowledge that encompassed new species and explored habitats and the movements and patterns of biota. It evaluated how abundance in the ocean is changing and might continue to change. In addition to the projects under the umbrella of the Census, this excitement has also benefited other collaborative and complementary programs to study marine biodiversity and ocean life.

Several thousand new species and growing, some formally named and some not – were discovered during the 10 year life of the Census, including the beautiful and bizarre, discovered in many parts of the ocean and from organisms spanning microbes to fishes (Figure 1.5). Indeed, the increase in the number of marine species may accelerate, as 5–10 years often intervene between when a specimen is collected and when it is formally described and honored with a name. Studies have expanded the
knowledge of the diversity of marine species and the evolutionary relationships among them. We know more about where they live and why they live there. The public has joined in the excitement, fascinated by wondrous new species, voicing concern over declines in species that they feed their children, and embracing the beauty of the ocean. We also now see more clearly what we know is unknown and what is “unknowable” with current technology and effort. Understanding the limits to knowledge of marine biodiversity guides science to what we can and must do. The Census has located and can now return to ocean environments, and their “hot spots” and “cold spots” of elevated or reduced biodiversity and abundance. We know where to look, and what ocean environments or habitats will continue to yield discoveries.

Insert Figure 1.5 here
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### Table 1.1 Maximum age estimates of individuals from the wild in various marine taxa

<table>
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<td><em>Sebastes aleutianus</em> (Rougheye rockfish)</td>
<td>Unknown</td>
<td>205</td>
<td>Ref3_C01</td>
</tr>
<tr>
<td>Echinoderm</td>
<td><em>Strongylocentrotus franciscanus</em> (Red sea urchin)</td>
<td>British Columbia, Canada</td>
<td>200</td>
<td>Ref4_C01</td>
</tr>
<tr>
<td>Bryozoan</td>
<td><em>Melicerita oblique</em></td>
<td>Weddell Sea</td>
<td>45</td>
<td>Ref5_C01</td>
</tr>
<tr>
<td>Arthropod</td>
<td><em>Homarus americanus</em> (American lobster)</td>
<td>Unknown</td>
<td>100</td>
<td>Ref6_C01</td>
</tr>
<tr>
<td>Pogonophorans</td>
<td><em>Lamellibrachia luymesi</em></td>
<td>Louisiana slope (~550 m)</td>
<td>250</td>
<td>Ref7_C01</td>
</tr>
<tr>
<td>Mollusk</td>
<td><em>Arctica islandica</em> (Ocean quahog)</td>
<td>North Icelandic Shelf (80 m)</td>
<td>407</td>
<td>Ref8_C01</td>
</tr>
<tr>
<td>Cnidarian</td>
<td><em>Leiopathes glaberrima</em> (Black coral)</td>
<td>Oahu and Big Island, Hawaii, United States</td>
<td>4,265</td>
<td>Ref9_C01</td>
</tr>
<tr>
<td>Sponge</td>
<td><em>Xestospongia muta</em> (Giant barrel sponge)</td>
<td>Curaçao</td>
<td>&gt;2,300</td>
<td>Ref10_C01</td>
</tr>
</tbody>
</table>
### Table 1.2  The projects within the Census of Marine Life

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oceans Past</strong></td>
<td></td>
</tr>
<tr>
<td>History of Marine Animal Populations (HMAP)</td>
<td>Use historical archives to analyze marine population data before and after significant human impacts on the ocean.</td>
</tr>
<tr>
<td><strong>Oceans Present: Geographic Realms</strong></td>
<td></td>
</tr>
<tr>
<td>Natural Geography in Shore Areas (NaGISA)</td>
<td>Inventory and monitor biodiversity in the narrow nearshore zone of the world’s oceans at depths of less than 20 meters.</td>
</tr>
<tr>
<td>Gulf of Maine Area (GoMA)</td>
<td>Document all species in a regional ecosystem and show how understanding biodiversity patterns and factors improves ecosystem management.</td>
</tr>
<tr>
<td>Continental Margin Ecosystems on a Worldwide Scale (COMARGE)</td>
<td>Assemble and understand the patterns of diversity on continental margins (slopes).</td>
</tr>
<tr>
<td>Patterns and Processes of the Ecosystems of the Northern Mid-Atlantic</td>
<td>Study the animals and their distribution on the northern mid-Atlantic Ridge.</td>
</tr>
<tr>
<td>Project Description</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Global Census of Marine Life on Seamounts (CenSeam)</strong></td>
<td></td>
</tr>
<tr>
<td>Explore seamount ecosystems, globally.</td>
<td></td>
</tr>
<tr>
<td><strong>Census of Diversity of Abyssal Marine Life (CeDAMar)</strong></td>
<td></td>
</tr>
<tr>
<td>Document diversity patterns on deep-sea abyssal plains.</td>
<td></td>
</tr>
<tr>
<td><strong>Biogeography of Deep-Water Chemosynthetic Ecosystems (ChEss)</strong></td>
<td></td>
</tr>
<tr>
<td>Study the biogeography of deep-water chemosynthetic ecosystems.</td>
<td></td>
</tr>
<tr>
<td><strong>Arctic Ocean Diversity (ArcOD)</strong></td>
<td></td>
</tr>
<tr>
<td>Inventory biodiversity in the Arctic sea ice, water column, and seafloor from</td>
<td></td>
</tr>
<tr>
<td>shallow shelves to deep basins.</td>
<td></td>
</tr>
<tr>
<td><strong>Census of Antarctic Marine Life (CAML)</strong></td>
<td></td>
</tr>
<tr>
<td>Survey life in the cold Southern Ocean surrounding Antarctica.</td>
<td></td>
</tr>
<tr>
<td><strong>International Census of Marine Microbes (ICoMM)</strong></td>
<td></td>
</tr>
<tr>
<td>Build a cyberinfrastructure to index and organize what is known about microbes,</td>
<td></td>
</tr>
<tr>
<td>which account for up to 90% of ocean biomass.</td>
<td></td>
</tr>
<tr>
<td><strong>Census of Marine Zooplankton (CMarZ)</strong></td>
<td></td>
</tr>
<tr>
<td>Assess biodiversity of the animal plankton, including ~7,000 described species</td>
<td></td>
</tr>
<tr>
<td>representing 15 different phyla.</td>
<td></td>
</tr>
<tr>
<td><strong>Pacific Ocean Shelf Tracking Project</strong></td>
<td></td>
</tr>
<tr>
<td>Develop and apply new electronic tags on salmon and other species to study how</td>
<td></td>
</tr>
<tr>
<td>they migrate along the Pacific.</td>
<td></td>
</tr>
<tr>
<td><strong>(POST)</strong></td>
<td>coastline.</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Tagging of Pacific Predators (TOPP)</strong></td>
<td>Apply new electronic tagging to track the migration of large, open-ocean animals.</td>
</tr>
</tbody>
</table>

**Oceans Future**

| **Future of Marine Animal Populations (FMAP)** | Project globally changing abundance, distribution, and diversity and the effects of fishing, climate change, and other influences. |

**Using the Data**

| **Ocean Biogeographic Information System (OBIS)** | Build an Internet-based bank of spatial information on marine species that brings together datasets from all around the world, adds new data, and is open to all to visualize how species relate and react to their environment. |
2

The ocean environments

The diversity of habitats in Planet Ocean has driven the evolution of life, its size, life span, mobility, and survival. We think of salt water and its immensity, perhaps seen from an airplane on an intercontinental flight, few seeing the distinct environments beneath the waves. When we think of what lives beneath the waves, we might think of whales and sharks rather than the 90% of total ocean biomass that is microbes.

A group of marine ecologists organized all the five oceans of the world and their habitats into 232 ecoregions, which have relatively homogeneous species composition, clearly distinct from adjacent ecoregions. Variables such as surface currents and bottom flow, which in turn define a suite of key variables from seafloor sediments to water temperature, differentiate these ecoregions. All form “One Ocean” that covers “Planet Ocean” and is “Home Sweet Home” to species evolving to adapt to their distinct habitats.

Scientists divide the ocean into the near shore close to land and the continental shelf less than about 200 meters deep. Further offshore, the
open ocean sits above the continental slope 200–4,000 meters beneath that
flattens to the abyssal plains at 4,000–6,000 meters below the surface.
Along with deep-ocean trenches as deep as 11,000 meters, the slope and
abyssal plains comprise the deep sea. Some argue that the true deep sea,
where the ocean’s surface and bottom are almost disconnected and the
influence of land typically fades, occurs near 1,000 meters depth, but the
precise demarcation varies with location and whom you ask. For those
rolling around on storm-battered ships hundreds of kilometers from shore,
this distinction is moot. The reality is that ecoregions form a continuum
that encompasses a variety of habitats, each with its own characteristics
and, in many cases, suites of species.

**Sampling the ocean**

Some parts of the ocean are relatively easy to sample. Because the
shoreline between high and low tides is easily accessible without ships or
complex equipment, even aboriginal man studied these habitats. Scuba
divers can safely access the upper 20 meters, but depths much greater than
that require specialized and expensive sampling gear, including boats,
ships, and oceanographic instruments. The development of satellite
sensors beginning in the late 1970s provided broad views of the single-
celled, plant-like photosynthetic organisms (*phytoplankton*) that live in the
surface waters, and new views of the temperature and circulation over
large swaths of ocean. These views spanned ocean basins from the near
shore to the open ocean.

But while satellites see wide swaths, they only see the upper few meters
or 10s of meters of the ocean, depending on the specific sensor used.
Satellites cannot see most of the ocean because it is some 3,800 meters
deep on average. Thus, most organisms are invisible to satellites. For
example, they largely miss the *zooplankton* (“drifting animals”) that
include a rich array of invertebrate jellyfish, shrimp-like crustaceans,
larval fishes, and other organisms. Though most are only centimeters or
less in size, many are abundant. Though the shallowest seafloor can be
seen with some types of special equipment mounted on satellites and
airplanes, water hides most of the seafloor and the life in and above it.

Traditional nets, bottles, and cameras that are lowered over the side of
the ship (see Chapter 4) have sampled the organisms that live farther from
shore in the opaque depths that comprise the more than 99% of the ocean
that satellites cannot see. Wind, waves, and surface currents push the ship
around as the samples are collected, adding to the challenge. It’s like
trying to sample birds and worms on land from a hot air balloon on a
cloudy, windy night.

The last decade has seen advances in ocean sampling as technologies
such as satellites, submersibles, and autonomous underwater vehicles
(AUVs) extended traditional sampling from ships. Submersibles and remotely operated, unmanned vehicles (ROVs) lowered from a ship and monitored from the surface open new “viewing ports” for sampling organisms and measuring environmental conditions. These vehicles are expensive, however, and few are available for scientific research. Even the oceanographic mother ships themselves are expensive and few. Because funds and distance has limited past research, sampling has often been during brief cruises, bringing back just snapshots and anecdotes about a tiny fraction of the ocean through space and in time.

Now, marine animals themselves carry sensors, “listening devices” enumerate organisms as they swim by, and other acoustic devices scan wide swaths of ocean water and seafloor (see Chapters 7 and 8). New imaging and statistical tools provide fresh views of data, and new molecular barcoding rapidly identifies species. Amid the staggering array of life in Planet Ocean in 2010, new tools are moving some key unknowns into the known, and some of the unknowable into the knowable.

Near the land

The nearshore and coastal zone, defined here as the seabed and the water above it from the upper intertidal zone to the edge of the continental shelf (between 100 and 200 meters deep, depending on location), covers only
about 7% of Earth’s seafloor. Nevertheless, together they support
imported habitats, including many fisheries such as Georges Bank and
tourist destinations such as the Caribbean and Thailand, as well as waters
rich and poor in biodiversity. Coral reefs, for example, support more
species per unit area than any other marine habitat and potentially any
habitat on Earth (Figure 2.1), whereas intertidal environments that teem
with abundance have relatively few species and little diversity.

The rocky intertidal habitats at all latitudes support species specifically
adapted to those environments. Terrestrial approaches to understanding
biodiversity are now applied in intertidal ecosystems. Because of their
accessibility, these environments are ideal laboratories to study how
climate change, invasive species, shoreline development, and pollution are
changing patterns of biodiversity and the ramifications of these changes.
Natural fluctuations in temperatures and salinity, strong waves, sediment
scouring (and sometimes ice) disturbance, and exposure to air in the
shallow nearshore and coastal waters create harsher environments than
those in deeper water. Many benthic species, those that are adapted to life
on the seafloor, cannot tolerate the fluctuations. Species that can tolerate
these conditions, however, find abundant light for photosynthesis and
fixed substrate for sessile (attached, non-mobile) organisms to settle on
and grow. These habitats yield much biomass (total mass of living
organisms) of benthos (bottom-living organisms) that includes seaweeds,
seagrasses and other plants, and invertebrates such as barnacles and mussels. In addition to the abundance of food, the hiding places around these fixed organisms provide protective habitat for a range of species that live above the seafloor – especially the young that are vulnerable to predators.

Estuaries have played a grand role in human history because they are where rivers meet the ocean, and the junction may provide drinking water and remove waste. At the junction, seaports load people, raw materials, and goods from oil to autos. Almost two-thirds of the largest cities in the world are built around estuaries (think New York, London, Athens, Tokyo, Vancouver). Many organisms that live in the extremes of freshwater or fully saline saltwater cannot tolerate the variable and brackish water in estuaries. The tolerant species, however, may grow abundantly on nutrients eroded from the land. Seagrasses, salt marshes, and mangroves shelter a variety of species, including vulnerable young.

Not surprisingly, excess nutrients and hypoxia, pollutants, overfishing, altered hydrography, and invasive species affect estuaries. Although in 1664 alewife ascended the rivers of New England “in such multitudes…as will scarcely allow them to swim,” most Boston residents know “Alewife” best as the name of a subway stop.
Nearshore ecoregions buried in mud and sand are less well studied than the rocky intertidal, but also matter for organisms and their productivity and nutrient cycling. Although buried habitats are also threatened by human activities, the cover of sand and mud teems with small invertebrates such as polychaete worms, crustaceans, and mollusks. This buried life feeds migratory birds and groundfish such as cod and halibut.

In mangrove forests in the tropics and salt marshes in middle latitudes, plants bind mud and create productive habitats that are home to specialized species, often as a nursery. Although many species in mangroves are marine, the vegetation that rises above the ocean’s surface also supports insects and birds, some of which feed on the small invertebrates in the sediment. Humans gather at the coastline; 3.6 billion people already live within 150 kilometers of the ocean, putting the near shore at risk. The gathering multitude intrudes into mangroves and salt marshes on the ocean edge, clearing plants for coastal development. Because shrimp mariculture, aquaculture in the ocean, displaces mangroves, it lessens biodiversity.

The shallow subtidal receives sufficient sunlight for photosynthesis by both single-celled phytoplankton and multicellular seagrasses, kelps, or other seaweeds attached to the seafloor. People who spend time on the shoreline know partially submerged seagrass meadows along sheltered
shorelines are often sensitive and important nurseries for juvenile fishes, feeding seabirds, and other species. Kelps, the large brown seaweeds with broad blades akin to leaves, support fishes and small animals that graze on them, as well as sea otters and other species that eat the smaller animals (Figure 2.2). Some subtidal habitats are less known, such as the hard-bottom rhodolith beds created by calcareous red algae that encrust the seafloor and, in turn, provide habitat for other species. All nearshore habitats support life adapted to that environment, and although some species live in a range of habitat types, others are specific in their needs and thus more vulnerable when habitat is lost.

Rich fisheries abound in nearshore areas. Hunting and fishing in the Wadden Sea for birds, marine mammals, fishes, and mollusks have fed coastal communities. Herring fisheries in northwest Europe, cod fisheries in the eastern United States, and salmon fisheries of the White and Barents Sea, that shaped nations, have dramatically declined, creating hardship.

I witnessed one of the “textbook” collapses in my own backyard. Explorers in the late fifteenth century caught Newfoundland cod just by lowering baskets over the side of the ship. But by 1992 fish were so scarce that fishing closed, as fishermen, scientists, and managers unanimously agreed that the stocks had collapsed. Overnight, the closure threw fully
22,000 of Newfoundland’s 510,000 people out of work, creating the
greatest industrial closure in Canadian history and in one of its least-
populated provinces. The calamity affected almost all the half million
inhabitants, including my own family.

Simultaneously, recreational fisheries elsewhere in the world sputtered
down, ending the money that wealthy tourists injected into localities to
catch once abundant “trophy fish” that are rarely or never seen today.

Today’s trophy winners might have been laughed at 50 years ago.

Increasingly, managers are finding that species beyond those they target
must be considered, to understand why some years are poor and others are
good for fishermen. This new “ecosystem-based management” recognizes
that the predators (including humans) and prey, food-web components,
and competitors in the rich diversity of the ocean all play roles as fisheries
collapse, and sometimes recover.

A diver or snorkeler on coral reefs encounters spectacular beauty and
variety (Figure 2.1). They sense special diversity of life on reefs. Coral
reefs require clear, sunlit shallow areas in tropical latitudes, but more
species have evolved on them than in other marine ecoregions.

Humanity continually interacts with life in temperate and tropical
coastal waters, collecting food, shipping freight, swimming, and gazing at
seascapes. Sadly, many activities threaten the beauty and diversity of coral
reefs and their function as natural breakwaters and coastal fisheries, putting them at greater risk than any ocean habitat on Planet Ocean. Our surprising lack of knowledge about life in these accessible reefs is an opportunity for discovery.

**The cold polar oceans**

The understandable ignorance of life in frigid waters opens exciting exploration. For collaborating Census explorers, the Arctic and Antarctic waters at opposite poles have similarities, but also contrasts. Ice generally covers polar regions in winter, shading life beneath it, even as endless nights give way to endless days (Figure 2.3). As the days lengthen, the ice retreats and sunlight penetrates the ocean. Organisms are adapted to year-round water temperatures that may be as cold as $-1.9\, ^\circ C$ without freezing, thanks to the salt. Exposure to cold water, shading ice, daylong darkness, and limited nutrients create an unproductive polar ocean that bursts to life for short periods leading up to endless days of midnight sun.

Similarities between the poles largely end there. Polar bears live only in the Arctic and penguins only in the southern hemisphere, meeting only in zoos and comic strips. Continents surround the Arctic Ocean basin and ice covers much of it, whereas the Southern Ocean surrounds the ice-covered Antarctic continent. These contrasts create a relatively shallow Arctic
Ocean with a wide continental shelf and basin averaging less than 1,300 meters depth, and with significant freshwater inflow. Currents meander around the edge of the basin and form large circulation loops called gyres, which interact with weather to affect organisms from year to year. In contrast, the Antarctic continental shelf is relatively narrow and the steep continental slope plunges onto the abyssal plain. The Southern Ocean surrounding the Antarctic continent circulates around the Earth unobstructed by land. In sailor’s terms, this open ocean creates infinite fetch (the distance the wind blows over the ocean), producing one of the fastest currents and some of the roughest sailing in the world. Little wonder that adventurers like Joshua Slocum spent weeks trying to pass Cape Horn!

Together these similarities and differences allow more than 6,000 species to live in the Arctic, Antarctic, or both. Although more diverse life is thought to live in the Antarctic region, neither the Arctic nor Antarctic has been well explored, and exploration of each continues to yield new species. Indeed, about half of the 1,400 invertebrate species sampled from the abyssal plain adjacent to the Antarctic were new to science. A warmer climate and some of the largest temperature changes are expected in the polar regions, and will melt ice and change food webs and ocean productivity. If warming alters circulation, these effects could be
worsened and circulation of pollutants such as mercury would surely change.

**Drifting plankton and swimming nekton**

*Plankton*, including microbes, eggs, larvae, and even jellyfish, drift passively at the mercy of currents. In contrast, *nekton* are animals like fish and whales that can make headway against currents and generally swim wherever they choose. Although fauna is typically more concentrated on the seafloor than in the water above, an array of life spends most or all of their lives in the water, drifting and swimming in a three-dimensional world. There is no parallel on land, where even birds rest on the thin veneer of terrestrial Earth that life occupies. Sunlight energy fuels photosynthesis in phytoplankton to create organic material, which in turn fuels most marine food webs. Small animals, the zooplankton, link the phytoplankton to top-level predators targeted by fisheries. Zooplankton also link, often through fishes, to the larger whales, sea lions, and sea turtles that people love, fearing their decline or even endangerment. The smallest and thus least-known plankton are the *microbes*, the mostly single-celled bacteria and protists. Microbes occur everywhere, surprising explorers who find them in rock 1.6 kilometers deep in solid Earth or at 300 °C in superheated hydrothermal vents. Despite their small size that makes them nearly indistinguishable even under a microscope, microbes...
provide key services and the ocean would die without them. Microbes fuel
some of the most productive fisheries, but they also spread disease, like
coliform bacteria, or they paralyze shellfish consumers, as some algae do.

Satellite images of vast blue ocean tempt us to assume that plankton
drift and nekton swim freely. Temperature and depth, however, create
invisible barriers that block traveling sea life, just as the absence of roads
on land blocks our traveling cars. These physical differences of
temperature and depth create rich fisheries in some waters and
unproductive ones elsewhere. Generally coastal waters, where runoff from
land, upwelling, and regeneration of mineral nutrients from the seafloor
can feed many fish and other life, has more food than the open ocean that
lacks these nutrient sources.

The differences between surface waters near the coast versus the open
ocean affect movement and thus distribution of large nekton such as
whales and seals, sharks, sea turtles, seabirds, and large fishes. Some
migrate seasonally to feed or reproduce, sometimes crossing entire
oceans. Some seabirds circumnavigate the globe. New tracking tools,
many pioneered by the Census, are clarifying why they migrate along
specific routes and whether they migrate to feed or mate.

Migrants like tuna that travel many kilometers for months respect no
international boundaries. No nation can regulate these migrants, obviating
national management and conservation. Like their counterparts in Newfoundland, tuna fishermen suffer along with their prey, although in this case it is a high-stakes game where each fish may fetch tens of thousands of US dollars. But the new tools for tracking animals offer foundations for logical management and conservation and thus less decline in fish and suffering by fishermen. Moreover, attaching small sensors to animals such as elephant seals that travel far and dive deep in the Antarctic, enables a new oceanography where organisms collect oceanographic data even in the open ocean far from shore.

The open ocean pelagic zone

Scientists call the open ocean the pelagic zone. It begins at the edge of the continental shelf near 200 meters depth and extends across the open ocean. Because the open ocean covers two-thirds of the Earth, its underlying continental slopes and abyssal plains comprise by far the broadest habitat on Earth, and the open ocean itself provides most of the livable habitat volume on Earth. Within the open ocean, geography, geology, physics, and biology create distinct habitats. The continental slope is closer to land masses so land runoff, much flowing down rivers to the sea, has greater influence than in the rest of the oceanic realm. During glacial periods, when sea level was lower, rivers
carved canyons, which join with other topography, ocean currents, and different productivity of the waters above to create complicated seascapes on continental margins. Fishermen catch grenadiers and Greenland halibut, among others, from the upper continental slope, but deep-sea trawlers must travel far, lose time lowering and recovering nets, and chase scarce fish. Deep-sea fisheries were too costly for most countries, but now the collapse of coastal fisheries and subsidized fishing encourage fishermen to venture into deeper and deeper water.

Sunlight does not penetrate onto most of the continental slope or the abyssal plains, where temperature and salinity vary little. Because darkness means no photosynthesis, the only food falls down from the sunlit surface, often passing through the digestive tracts of mid-water organisms. As it sinks, it is degraded further by bacteria. This food is poetically described as *marine snow*, bits of organic matter sinking from surface waters above. Bottom currents may supply decaying kelp and similar food from productive areas of the continental shelf, but less and less food snows down as distance from land increases.

The pressure of water is immense, reaching several hundred times surface pressure on the abyssal plains. As animals with lungs or sinuses filled with air dive to feed, they must cope with these pressures. If a submersible hull failed, this high pressure would crush passengers before
they had a chance to drown! Because pressure modifies how some
molecules work, the specialized *enzymes* that facilitate chemical reactions
in deep-sea organisms differ from those evolved in shallow water.

High pressure, darkness, and no photosynthesis create an inhospitable
environment for life. Thus, the deep ocean was once thought to be a
desert, devoid of life. Indeed, early photographs of the deep sea revealed
vast plains of gently rolling seafloor covered in sediment (*Figure 2.4*),
propagating the analogy of the abyssal desert that is just now disappearing
from textbooks. Today we know that many species live within the
sediments, spanning invertebrates, such as polychaete worms, nematodes
(thread worms), small clams and snails, sea stars and brittle stars, and
shrimp-like crustaceans. They move between the sediment grains and feed
on bacteria and bits of degraded food that sink from above. Limited food
may limit abundance, but it does not limit diversity. Indeed, far from it.

Exploration of the deep reveals more than rolling plains of sediments.
Protruding bedrock provides homes for deep-water corals and other
species that require hard surfaces instead of shifting sediment. Large beds
of deep-water corals, first discovered off the coast of Norway, form
beautiful, dense stands that are important habitat for deep-water species.
Census studies around the world on underwater mountains called
*seamounts* find corals too, some sparse and some dense. Unlike corals that
build reefs in the shallow tropics, corals in the deep, dark ocean lack
photosynthetic organisms in their tissue, and instead must feed on passing
marine snow and small animals.

As many as 40,000 seamounts rise 1,000 meters from the seafloor, and
200,000 rise more than 100 meters above the abyssal plain. Those that rise
above the water can form chains like the Hawaiian Islands. Mid-ocean
ridges, are long, submarine mountain chains that extend thousands of
miles through the ocean, rising from joints between the plates covering the
Earth, as magma flows and spreads to form new crust. The best-known
underwater mountain chain, the Mid-Atlantic Ridge, stretches 10,000
kilometers from Antarctica to Africa, and north past Greenland into the
Arctic. Occasionally it protrudes above the ocean’s surface to form islands
such as the Azores and Iceland. The Azores extend about 5,000 meters
above the abyssal plains that surround them, which does not quite match
the height of Mount Everest at 8,848 meters, but does illustrate the scale
of ocean ridges.

Fish-finding echosounders led fishermen to seamounts, where nutrient
upwelling, accelerating currents, and recirculation attract fish. Seamounts
are volcanic in origin and steep sides shed sediment, exposing hard
substrate. Cold-water corals and other attached organisms trap food as
water flows past and build three-dimensional habitats. Fishermen catch
abundant fish around seamounts. Seamounts sometimes support different species than the surrounding abyssal plains, and some chains of seamounts have species not found anywhere else. Census research on the Mid-Atlantic Ridge suggests little endemism, where species are unique to that location. Nonetheless, some seamount populations may sometimes evolve in isolation from similar populations at distant seamounts, much like the finches on the isolated Galápagos Islands illustrated the idea of evolution in Charles Darwin’s *Origin of Species*. Because so few have been sampled, more exploration of seamounts and mid-ocean ridges would likely bring much unknown into the realm of known.

Seamounts create isolated mountains in the otherwise muddy, rolling hills of the abyssal plains and thus support specialized deep-sea faunas. Their depth and distance from land makes scientific expeditions difficult to mount. But recognizing them as a frontier rarely explored, and a laboratory for understanding ecosystems scarcely altered by humans, scientists are leading a new surge of interest.

Small hydrothermal vents first discovered in 1977 flow at the edges of tectonic plates. While the edges of some plates ooze and spread new crust, others collide, and one plate is pushed beneath the other in a process called subduction. Subduction destroys the old ocean crust that moves deep into the Earth. During spreading and subduction the ocean crust
cracks, letting seawater percolate into the upper mantle, where it is
superheated and enriched with metals and other compounds. When the
fluid reemerges into the ocean, it can be 300–400 °C and rich in hydrogen
tsulfide, methane, carbon monoxide, and metal ions that are toxic to much
marine life. The discovery of a huge biomass (kilograms per square meter)
of meter-long tube worms and giant clams in the seemingly toxic waters
around vents (Figure 2.5) astounded scientists because, with a few
exceptions, the deep sea typically has few small organisms. An American
gossip magazine known for its exaggeration once interviewed Fred
Grassle, but the story of hydrothermal vents was so fantastic that they
reported it accurately without embellishment. Truth stranger than fiction!
But the subsequent discovery that the giant worms and clams were made
possible by bacteria living inside them that utilize chemical energy in the
vent fluid excited scientists even more. This discovery, made decades ago,
ended the view that all ecosystems are fueled by photosynthesis. In vent
ecosystems, specialized bacteria and archaea use chemical instead of
sunlight energy to create organic molecules that are the basis of life.
Ocean cold seeps, where methane, hydrocarbons, and hydrogen sulfide
slowly bubble from the seafloor and fuel bacterial production, also
support a large biomass of organisms.
During the 30 years of study since the discovery of vents and seeps, more than 700 species have been discovered at hydrothermal vents, and 600 species at seeps. Carcasses of whales that fall to the seafloor provide potential stepping stones between vents and seeps, but also support species unknown elsewhere. Even during the first decade of the twenty-first century, long after the Age of Discovery, Census explorers found new vents in the Arctic and Southern Ocean, moving unknown into known and raising the number of known species, a prelude to the riot of species in the many environments of Planet Ocean.
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A riot of species from microbes to whales

Centuries after the Age of Discovery, scientists still typically describe about four new marine species every day, not even including new microbes. Hydrothermal vents alone yield a newly described species about every two weeks and recently 90% of invertebrates species found in one area of the abyssal plains were new species. Explorers continue to pull new and once “extinct” species from the sea.

Recent discoveries include new fishes, lobsters, bizarre crabs, small crustaceans, octopuses, specialized worms, and carnivorous deep-sea sponges (Figure 1.5). They include sea cucumbers that walk across the seafloor, and a whole array of microbes from the Antarctic to deep-sea hydrothermal vents. Rarely explored habitats from the poles to open ocean waters, to deep-sea sediments, trenches, deep-ocean ridges, and hydrothermal vents added to the total, but only scratched the surface of the unknown species in these places. Skilled explorers are few, so discovery is slowed by how much these few experts can do and not by the large pool of undiscovered life.
Familiar coastal waters or intertidal pools along developed nations scoured by scientists for centuries unexpectedly raise the total of new species even more. For example, in 2006 a customs officer in Durban, South Africa relayed to Census scientists Johan Groeneveld and Charles Griffiths a fisherman’s request to export what were labeled as European lobsters. But European lobsters did not occur anywhere near where they had been fishing. The 4 kilogram lobster the fisherman wanted to export were discovered to be new to science, even though South Africa marine fauna is well studied.

Fishes, which are among the best-known marine life, add about 150 species per year. And discovery is not limited to rare species. The most numerous photosynthetic organism in the world, a small single-celled bacterium named *Prochlorococcus*, was unknown until 1985 when electronic “noise” turned out to be an unknown, but widely distributed and abundant species invisible under most microscopes, but detectable with lasers.

We now know that the oceanic riot of species will eventually number in the millions, an immense diversity. During the past 100 years, improved technologies have raised the projected number by making us more efficient explorers. But there is uncertainty. Scientists even debate
whether hundreds of thousands or many millions of species live in the ocean.

Unquestionably a greater diversity of broad groups of animals live in the ocean than on land or freshwater. Some animal phyla, a broad grouping of similar types of organisms such as the Echinodermata, including sea stars and sea urchins, live throughout the ocean, but not on land or in freshwater. But at the species level, the question of where most species live remains open. We are a terrestrial species that favors exploration of land over sea. The many tropical terrestrial insects, also mostly unknown, might tip the scales toward land. In the sea, mammals are the best-known group, and the fish are also comparatively well known. Nevertheless, new species of fish continue to be found in the Caribbean with no sign of slowing down since the 1700s, when descriptions started to accumulate. Many scientists believe that most marine diversity has not yet been sampled and described.

Just what is a species? Although most people would answer correctly that humans, chimpanzees, and dogs are separate species, the answer becomes harder when all organisms are considered. We typically define species as populations that at least have the potential to interbreed. Asexual reproduction in many single-celled species that simply divide or split off tissue fall outside this definition. Sexual breeding can be difficult
to confirm, and is particularly problematic to test among look-alike species. Also in \textit{sexually dimorphic} species, where males and females appear very different, the sexes are easily interpreted as separate species. Developmental stages such as caterpillars and butterflies on land might be mistaken for different species, and at sea, stages of a single species of jellyfish have frequently been called distinct species. Finally, because of the problem with the typical definition of species, microbiologists now often finesse the problem by referring to \textit{operational taxonomic units}, or OTUs, rather than species. OTUs are genetically distinct and assumed to be different from other OTUs. So what marine diversity is known?

\textbf{The history of exploration of marine biodiversity}

Human naming and drawing of life dates to the earliest recorded communication. Consider the \textasciitilde{}4,000-year-old drawings of dolphins on the palace walls at Knossos in Crete, and sturgeon on fifth-century BC Phoenician coins. About 350 BC Aristotle recorded and named hundreds of marine animals in his \textit{History of Animals}, so he became the “father of marine biology.” Practically, naming animals communicated which could be eaten and which were dangerous. Clues suggest harvesting of shellfish and finfish began in the middle Stone Age. Second-century Latin and Greek verse suggests trawling by Romans, who must have sorted the trawl contents into edible, ornamental, and poisonous.
Uncoordinated naming of which species was which created a Tower of Babel among regions and languages. Different cultures, and sometimes even each tribe and village, called species by a different name. Thus, how could a naturalist collecting codfish off the coast of Cape Cod be certain it was the same species being fished and marketed as torsk in Denmark, dorsz in Poland, and bacalhau in Portugal?

Almost 300 years ago the Swedish botanist, zoologist (and physician) Carl Linnaeus invented binomial nomenclature. Wisely avoiding argument about which modern language to use, the Linnaean system speaks in the near-universal Latin language. The system organized the Latin names in a hierarchy according to similar appearance, which Linnaeus attributed to God’s greater plan. Fortunately, that similarity usually reflects evolutionary relationships among species. For example, Gadus morhua, the binomial name of Atlantic cod, begins with the genus Gadus (which is also the genus for several closely related species of cod). The addition of morhua forms the unique species name Gadus morhua.

During his lifetime, Linnaeus classified many species as he expanded his initial 11 page Systema Naturae to more than 3,000 pages in the 13th edition. Understandably, he and many others changed some classifications as new information arrived, particularly about evolutionary relationships. Linnaeus had only the physical appearance or morphology for his
classification, and we know now that some species vary in appearance and
some genetically separate species look alike. In species where males and
females are completely different, physical appearance is almost useless for
inferring they are the same species. During the last few decades, some
problems were resolved with unique enzymes called *allozymes* and then
revolutionary molecular tools, such as barcoding, to rapidly identify
species. These new tools built on Linnaeus’ work to change biology
forever.

Following early waders near the shore, the history of ocean exploration
reached Phoenicians, Polynesians, and Vikings, and then European
explorers to the New World. Because early exploration sought new lands
and sea routes, navigation, coastlines, and currents were of first interest.
Nonetheless, the logs of early explorers such as Columbus and Caboto
record an abundance of fish and presence of large animals such as whales
and seals that suggest a world unlike our modern one. The widespread
name Tortuga (meaning turtle) for hundreds of islands, keys, and
headlands confirms records in ships’ logs of abundant turtles. Delving into
such historical information, the Census program *History of Marine Animal
Populations* (HMAP) created the new scientific discipline known as
environmental history, which recreates the ocean past.
Coordinated scientific investigations on marine expeditions began during 1700–1900. Such expeditions as James Cook’s focused primarily on physical measurements of bathymetry (seafloor depth) and ocean currents, but increasingly expeditions included naturalists. They collected specimens from the ocean as well as from land, along the shoreline and in deeper water using crude nets. Sailing on the HMS Beagle (1832–1836) inspired Darwin’s revolutionary theory of evolution, but as the Beagle sailed from Africa to South America to Australia, Darwin also made important collections and observations on marine species such as corals.

The scientific leader of another influential expedition, Charles Wyville Thompson, on the HMS Challenger (1872–1876) had already led several deep-sea expeditions that proved the existence of life in the deep. The Challenger voyage was truly global, traversing the Atlantic, Pacific, and Southern Oceans. The diversity of life in a wide range of ocean habitats reported in the 50 volumes and 29,552 pages of the Challenger Reports comprise a scientific achievement not since repeated. At a cost of well over 10 million pounds in today’s currency, it was truly a remarkable investment for its time. Indeed, the comprehensive and coordinated sampling detailed in the Challenger Reports stands as a model for the 10 years of exploration of the Census.
But the twentieth century saw the disappearance of large multiyear expeditions on the scale of the *Challenger* expedition. The cost of mounting such expeditions, and the availability and willingness of scientists to disappear for years, has effectively eliminated that model. That the examples of Darwin, seasick for the early stages of the *Beagle* voyage and Wyville Thompson’s death at age 52, exhausted by leading and reporting on the *Challenger* expedition, are not lost on those of us who study the oceans! Importantly, the naturalists who led research activities in the 1800s had obligations to a specific employer for collecting and reporting on the material from the expedition. Today, however, ocean explorers work for universities and governments and have research and teaching commitments that preclude voyages of months or years. Further, few governments are willing to invest tens of millions of dollars in a single voyage around the world! Thus, oceanographic voyages, euphemistically called “cruises” today, are rarely longer than days to a month or two, rather than the 41 months of the *Challenger* expedition.

**Exploration of marine biodiversity today**

Although grand expeditions like the *Challenger* have ceased, today marine ecologists have advantages over those who studied the ocean a century ago. With technologies like satellites, underwater cameras, submersibles, and a whole range of sensors, modern explorers can see the
ocean better than just by working over the side of a ship (Figure 3.1).

Telephones, computers, and data transfer, often wireless, speed communication and create the potential for international collaboration like the Census, which would have taken many years to coordinate in the past. Communication with and data transfer from scientific instruments and even diving animals like sea lions far away is becoming routine. The Challenger expedition reported in dusty published tomes stored in the recesses of libraries scattered all over the world. But everyone can access the Census discoveries at the Ocean Biogeographic Information System (OBIS, www.iobis.org), an open-access, globally distributed network of taxonomic, environmental, and geographical information, with a double click online.

OBIS and other Internet sites have coordinated taxonomy and developed identification tools. Unlike printed identification guides and keys in books, Internet guides can be updated quickly and inexpensively, and users instantly notified. Digitized information on the Internet linked through the Census partner project Encyclopedia of Life (EOL, www.eol.org) has removed the need to track down obscure monographs or journals in distant libraries. Ecologist E.O. Wilson, who imagined “an electronic page for each species of organism on Earth, available
everywhere by single access on command,” inspired EOL. Its “species pages,” once completed by specialists on that species, will provide instant links to published and unpublished material. EOL exemplifies how electronic communication accelerates the assembly, communication, and revision of knowledge and thus the movement of unknown to the known.

Up-to-date information like ever-improving species pages and taxonomic keys avoids mistaken identities that might take decades to resolve. Worse, the stain of unresolved mistakes propagates, even in the published literature, spreading quickly, while the origins of the error fade.

Internet tools help marine ecologists who are not specialized taxonomists provide accurate knowledge of species resting on the soundest information about who’s who in the ocean. Because species Web pages can link to related articles, efficiency improves because students of a species do not have to start from scratch assembling available information from widely scattered sources. Keep in mind the addition of something like 1,635 new marine species every year, and a single marine sample can contain dozens or even hundreds of unique, but easily confused species, initiating errors that quickly spread. Modern computers help stay on top of the burgeoning, mind-boggling information that once arrived in books, printed journals, and snail mail.
New molecular techniques differentiate among species, even look alike species, and accelerate discovery. Because many microbes look alike, molecular techniques have opened up a previously unknown world of microbial diversity. Indeed, the opinion that for microbes “everything is everywhere,” is now questioned. Individual species or different strains of a single microbial species can look identical, but have profoundly different impacts. For example, the toxic forms of the dinoflagellate (a single-celled protist) that causes red tides and paralytic shellfish poisoning are indistinguishable from benign strains, except by genetic analyses.

These techniques also help evaluate evolutionary relationships among species, and even among places.

The Census differentiates species with barcoding technology, a unique identifier like the barcodes at grocery stores. Barcodes, using a segment of the cytochrome oxidase I (COI) gene from a cell’s power pack, its mitochondria, differentiate most species of animals, both on land and in the water. Barcodes can rapidly tell us whether two specimens are the same species with relatively little ambiguity. When a library of barcodes has accumulated, any specimen can be identified by sequencing this gene and matching its barcode to one in the library. The Census partner project Marine Barcode of Life (MarBOL, www.marinebarcoding.org) is compiling a marine library and expects to accumulate reference codes for 50,000 species by the end of 2010. Barcoding will quickly and reliably
determine whether any newly collected specimens have already been
cataloged. Barcodes will minimize past confusion that regional variability
causes in the appearance of some species and similarity in the appearance
of others. For example, the shape of exposed kelps differs from the shapes
of sheltered ones, but transplanting to a contrasting environment causes
them to grow in a different shape adapted to the new flow conditions,
something known as *phenotypic plasticity*. Barcoding tells us they are the
same species, despite variation in form. Barcodes and their library will
identify samples collected from unexplored places that have no taxonomic
keys or experts. Barcodes and their library will help draw global maps of
species distribution.

By avoiding mistaken identity, barcoding can help avoid confused
management. When high-school students collaborating with the Census
sampled fish markets and restaurants in New York City, their barcoding
found cheap, farmed fish labeled as expensive wild species, and an
endangered species sold as a common one.

Contaminants in blue mussels are used to monitor coastal environments
around the world. But three blue mussel species look alike and their
distributions overlap, but different growth rates and physiologies.
Similarly, *Montastraea annularis*, the most widespread and studied coral
in Caribbean reefs, encompasses sibling species that look alike, but grow
at different rates. Confusion of species with different numbers of
offspring, age at maturity, and growth confuses management because
these characteristics dramatically change how quickly populations break
down contaminants, or grow and replace themselves.

The recent rapid advance in the *Geographic Information System* (GIS)
maps where organisms live. GIS speeds biodiversity studies, first by maps
and then by visualization described below. GIS puts biological samples at
the correct latitude and longitude, where overlaid maps of depth and
temperature help us understand why species live where they do.

Comprehensive maps of life on the abyssal plains, at hydrothermal vents,
or at the poles hinge on such tools. Although GIS technology works best
in two dimensions, advances promise that the three dimensions of the
ocean will soon become visible. For example, Google Earth already
displays Census observations in their Ocean layer.

Where are the hot spots of diversity, where are fishing impacts
pronounced, is climate change redistributing species, and where and why
do animals migrate? GIS helps draw overlays of environmental variables
on maps to test predictions about the changing distribution and abundance
of ocean life.

Internet databases, including the Census’ OBIS, are built on accurate
latitude and longitude. Formerly, explorers sampled at sea and published
their observations. Integrating such observations into a broader geographic perspective assumed similar quality of identification and uses of species names by others, and that they would share their data. This left much data on file cards, yellowing datasheets in file cabinets, or on computer hard drives around the world, that are often lost as experts retire.

Accordingly, “data rescue” avoids repetitive research and builds multiple datasets into larger, more comprehensive analyses, all without additional months of sailing and steaming. These metadata analyses, using data from multiple sources, look at global or other broad patterns because few individuals can collect enough data for broad comparisons across space or time. With long stretches and vast depth, Planet Ocean frustrates lone researchers. The Census repository OBIS therefore amalgamates separate datasets from around the world to archive the lasting legacy of marine biodiversity to analyze on regional to global scales. Sound metadata analyses need the correct GIS locations and verified names in OBIS.

Bringing together experts from many countries, shores, and seas, along with their ships and tools, the Census coordinated a global series of interlinked expeditions. Linked projects developed genetic barcoding tools, mapping techniques, global databases, and assembled samples for the world’s first global Census of Marine Life.
How many species live in the ocean?

Censuses, beginning with the Domesday Book collected for William the
Conqueror, count the single species of humans and tell us which are
barons, villains, or priests, and who has fish ponds and hides. In this spirit,
the question of how many species live in the ocean is at the core of the
Census of Marine Life. Even after a decade of intense research built on
centuries of exploration, however, a precise answer is still elusive. The

Nobel Prize winner Ernest Rutherford stated that, “All science is either
physics or stamp collecting.” Some regard biodiversity studies as a futile
“hobby” of stamp collecting, not too different from compiling lifetime
lists of birds spotted.

Recently, however, reports of species extinctions, and hence lost
biodiversity along with ecological services, have made biodiversity
knowledge valuable to Planet Ocean’s top carnivores, humans. Sympathy
grows for losing species before they are known to exist. Finally, most
people recognize the value of knowledge, irrespective of economic payoff
or impact on ecosystems.

Understanding what lives in the ocean begins with answering how
many marine species scientists have named. How many marine species
are known so far? Several recent analyses suggest somewhere between
one-quarter and one-third million. A less ambitious, but necessary, first step is compiling global lists of species for a few major groups such as fishes. Most group lists are regional ones that overlap other lists and do not always identify organisms accurately. Is a specimen called species X from one location the same as one called X elsewhere? Or, are species called X and Y in different locations actually different? There are numerous examples of closely related sibling species that look alike, but have distinct biology and genetics.

Unaware what others have done recently, errors are made. Because scientists discover 1,300–1,500 valid new marine species every year, the reference list of known species constantly shifts. The shifts require frequent updates of keys and guides and render paper publications out of date as soon as they come off the press.

Fortunately, e-mail runs faster. Tracey Sutton, a Census fish specialist collecting in the South Atlantic, could hardly believe his luck when he looked at the animals in a trawl and realized that one of the juvenile fishes was intermediate between two families of fishes (Figure 3.2). E-mailing a photograph of the fish to an Australian colleague, he learned that the oddity was the final missing link to a puzzle they were putting together with a collaborator at the Smithsonian Institution. Genetic confirmation proved that three “different” groups of fishes with very different
anatomies, previously thought to be totally different taxonomic families, are actually the male, female, and larval stages of closely related fishes from a single family.

Photographs can confuse as well as resolve. Fuzzy photographs of a worm-like deep-sea animal assigned to the phylum Hemichordata, led biologists to think it represented a missing evolutionary link between two groups. But when a specimen of the since-named *Torquarator bullocki* replaced the fuzzy photograph, the mystery was solved. Though not the expected missing link, it was a new species, a new genus, and a new family.

Taxonomists may specialize in identifying a group as broad as all polychaete worms or, more frequently, they specialize in a smaller subset. The number of trained taxonomists is few, and is declining as museums cut budgets and retiring experts are not replaced. Dedicated amateur hobbyists augment these professionals incompletely and unevenly, specializing in just a few groups, such as shelled mollusks and crustaceans, and leaving other groups to the shrinking handful of professionals scattered around the world. Because amateur taxonomists mainly see land species, between 1998 and 2005 they described only 10 to 15% of new European marine species, far less than the 46% of new land
and freshwater insects they described. This neglect of the oceans contributes to the naming of new species in the ocean lagging far behind naming on land, despite great diversity in the ocean. Further, the location of most taxonomic expertise in Europe and North America does not match the location of the bonanza of new species found and to be discovered near tropical, developing countries.

Most specimens are collected by ecologists in their net tows and bottom grabs, and they try to identify everything they catch. This scope means they must identify species from many taxonomic groups. Although their knowledge may be broad, they are not attuned to spotting new species that are easily confused with known species. Simple mistakes in spelling or taxonomists changing species names can further confuse ecologists’ lists. The good fortune of working with a taxonomist improves ecologists’ chances, but they rarely have expert partners for the multiple groups they encounter.

The World Register of Marine Species, or WoRMS (www.marinespecies.org), works with the Census, EOL, and OBIS, and the global list of species rapidly improves. The organizations expect to confirm more than 200,000 valid, distinct species by the fall of 2010 when this book is published. This goal can be achieved because experts on
many organisms worked together, carefully examining every species to be
certain it is unique and valid.

Putting aside the problem of misnamed species that the collaborating
organizations hope to solve, I return to the still unanswered question,
“How many unknown species live in the vast, thinly sampled ocean?” A
wise answer recognizes the biases that affect the count as descriptions of
new species in the ocean proceed and discovery moves the unknown to
known. First, census-takers count big and ostentatious organisms better
than small, hidden microbes and invertebrates. Second, tropical oceanic
islands, polar waters, seamounts, and the deep sea far from developed
costlines are more thinly explored than accessible areas like the
European coastline. The tricky problem of estimating numbers of
unknown species has inspired several strategies, each with limitations.

Extrapolating the rate at which new species are now being discovered
can project future discoveries in groups where most species are known.
For example, if new species are rarely added, as is now true for marine
mammals, then it is fairly safe to conclude that future exploration will add
few. But both accelerating and even continuing rates of discovery make
projections difficult. In Figure 3.3, the curved thick line on the plot
represents one geographic region or one group of organisms that is
beginning to level off, making 100 a reasonable estimate of the total
number of species. But if the curve for a region or group has not begun to
plateau, like the straight thick line, then there is no way to know how
much higher it will climb before it eventually levels off. Its total could be
500, 1000, or many more. Also the slopes of the curves will rise faster or
slower depending on how many people are describing new species.
Projecting the number of species and thus diversity in the ocean suffers
from the timeless conundrum: When will a trend end?

Fishes provide a specific example of numbers. A thorough global list
(www.fishbase.org) resting on the widespread counting of fish makes
possible a precise estimate of 16,475 species. The evident rate of
discovery and its deceleration enable extrapolation to the eventual total.
The Census project, the *Future of Marine Animal Populations* (FMAP),
did exactly this for fish, where they estimated that 21% of all fishes in the
ocean have yet to be discovered. They estimate between 1,000 and 4,000
more species to be found, depending on the statistical model. Not
surprisingly, because some environments are less known than others, the
deep-sea *bathyal* (1,000 to 4,000 meters) and *demersal* (seafloor) habitats
as well as the tropical environments are yielding and will continue to yield
most new species of fishes. Even this relatively certain estimate for a
well-known group rests on incomplete data and erroneous names. Also,
scientists believe that Caribbean fishes are actually not well explored and may yield many more species than predicted with this approach.

The expert opinion of taxonomic specialists for specific groups provides an alternative. An expert on marine mollusks who has studied specimens from a variety of environments could estimate how many new species are typically found when new environments are explored and then extrapolate globally. If experts from groups of organisms are asked for estimates for their group, pooling those estimates together or scaling upward from well-known groups to all groups can build an estimate of the total number of species in the ocean. This approach estimates 500,000 to 1,000,000 multicellular species. Still another approach adds ocean habitats geographically. Because many experts focus on one type of habitat, such as coral reefs, or particular groups of organisms that are more common in some habitats than others, their estimate of unknowns for that habitat or group is more accurate. This approach estimates that, not including microbes, coral reefs alone may be home to 600,000 to 9.5 million species.

Asking how many new species will be found if more ocean is explored forms still another estimator. Exhaustive sampling presumably finds all species in a small lake, for example, or reaches the point where the unknown species can be estimated with reasonable precision. Fred Grassle
and Nancy Maciolek performed this analysis for the deep sea in 1992. They estimated the number of macrofaunal species, the invertebrates such as polychaete worms and mollusks from 0.3 millimeters to several centimeters, regionally and globally. They compiled the most complete dataset of its time for all macrofauna from any region of the deep ocean. They sampled primarily along a depth contour at 2,100 meters, adding species with each new sample and distance along the contour.

Grassle and Maciolek reasoned that rates of adding species along a constant depth should conservatively estimate how more exploration will lift the total of new species. Extrapolating from their area of exploration along the 2,100 meter contour out to the rest of the deep sea, they estimated 100 million species. Because the abyssal plains have few macrofauna, they scaled back their estimate by an order of magnitude to 10 million species.

This estimate prompted debate whether ten million was too high or whether including smaller meiofauna such as nematode threadworms and tiny crustaceans (less than 0.3 millimeters, but larger than 0.04 millimeters), would raise the estimate. A critical question is which species are cosmopolitan, or widely distributed geographically. Rapidly changing composition with geographic distance would raise Grassle and Maciolek’s estimate, whereas slow change would lower it. One specialist who
estimated 100s of millions of deep-sea meiofaunal species later
downgraded the estimate to less than one million, since many are
cosmopolitan.

Others proposed estimating unknown marine species numbers by the
percentage of new species found in each study. A criticism of the Grassle
and Maciolek estimate was that they found only 58% of their species were
new to science. Extrapolating that percentage by the number of described
species in the ocean suggests that the deep sea contains perhaps 250,000
macrofaunal species. The major caveat with this use of published studies
is that not all areas have been studied equally, and in the deep South
Pacific the proportion of new species was as much as 95%, and suggested
an extrapolation of 500,000 macrofaunal species was more appropriate.

Because the estimate of 10 million is the number of species in the deep
ocean, answering how many species live in the entire ocean brings a
larger number. Exploration of places other than the deep sea also adds to
the total of marine species. For example, 20% of European gastropods
(snails and related organisms) were described within the last 25 years,
which extrapolates to 11–50% of European marine fauna remaining to be
found. Mollusk expert Philippe Bouchet found more mollusk species in a
single 30,000 square-kilometer area of the tropical Pacific than are known
for all of the Mediterranean, which is 10,000 times larger!
Encompassing the wild card of microbes in the count of species will also add to the number of species in the ocean, greatly. Whether species are widely distributed is least known for smaller organisms. Microbial experts argue that a single drop of seawater may hold 160 types of bacteria, and in the deep sea a liter of seawater may hold a few thousand types of microbes, including rare forms represented by a few or even one individual. Protistologists argue whether protist distributions are cosmopolitan, but the few sparsely distributed samples of such organisms cannot possibly resolve the debate. Given that little of the ocean has been sampled for microbial diversity, how is it possible to scale up samples from a few liters of water or sediment to the entire ocean? At this point it isn’t, at least without more sampling. By analogy, imagine trying to estimate the number of species on an entire continent based only on observations from your own backyard!

While Bouchet estimated that known marine biodiversity represents about 15% of all species on Earth, he also noted slower discovery in marine than terrestrial fauna. He calculated that explorers will spend 250 years to a millennium to finish inventorying marine biodiversity, ignoring microbes, hindered by limited exploration and taxonomists. In recent years, some countries have prohibited foreigners from sampling in their territorial waters because biodiversity may have unknown economic potential. Because poorer countries lack the scientific capacity to explore
their own waters, the global ocean may not be explored for a long time.

Still, the emerging tools described above will help to shorten the time, but the time will remain long and will depend on how quickly poor nations can develop scientific capability.

To accelerate the taxonomic tide to Bay of Fundy speed, the Census of Marine Zooplankton (CMarZ) sponsored some 27 taxonomy workshops involving 253 taxonomists who marry traditional morphological taxonomy with barcoding. Online resources and imagery such as the EOL, in tandem with accurate inventories such as WoRMS and online keys and databases will also make taxonomy easier and more precise. These efforts will shorten century-long projections. Moreover, the excitement from Census discoveries such as the Yeti crab (Figure 1.5a) and other species found near and far during the last decade will inspire marine exploration.

Even a large, international program like the Census of Marine Life pushes the frontier of the known forward slowly. Although experts continue to argue about the magnitude – even the order of magnitude – of marine biodiversity, the numbers rest on more facts. Ignoring the wildcard of microbes, some scientists would probably be comfortable saying that there are at least one million species in the ocean, or maybe several million. Accuracy, or closeness to the real value, depends on knowing the level of uncertainty in those predictions, which new statistical models...
improve. The new technology examined in the next chapter will expand
the span of exploration, making extrapolations more accurate and
defensible.
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Part II

The known: what has the Census learned?
Chapter 4

New ways of seeing deeper and farther

For millenia, wading and sailing humans have collected ocean life to eat, and to cover and decorate themselves. They collected it for fuel and fertilizer. As burgeoning populations intensified harvesting and grew more dependent on marine life, their efforts to understand where organisms live and why they live there also grew. Fortunately, physics, geology, and chemistry advanced in parallel, improving technology for seeing deeper into the once opaque ocean, even to the ocean bottom.

The once opaque ocean

Google Earth shows the sunlit yard behind our homes, but sunlight penetrates only hundreds of meters at best through water. Sailors see little over the rail. The optical tools we lower into the ocean “see” only a few tens of meters through water before images become fuzzy and useless. New technologies and tools now peer farther into and across the ocean in ways that seem like Jules Verne’s science fiction. To answer its questions, the Census invented some tools and adapted others. Other explorers...
independently developed tools. The new toolbox makes the once opaque ocean more transparent, clarifying the view deep below the surface.

Vast, fluid, and moving, the ocean runs far and deep. Swimming and drifting marine life travels among continents or inhabits hidden habitats far from shore, at great depths, or in very specialized habitats that are difficult to sample. People dive far less deeply into Planet Ocean, and see only a tiny fraction of the ocean before generalizing from their limited glimpses. It’s like 60 second dating, where glimpses transform lives.

Planet Ocean will not shrink – if anything, rising sea levels will expand it. This means we must become smarter to see deeper and farther. Ships still carry us to different seas, where we lower buckets and nets into the depths beneath. More than a century ago, when HMS *Challenger* set to sea, researchers were sampling almost blindly because they knew little about what lay beneath. They were less afraid of sailing over the Earth’s edge or monsters rising from the deep than Columbus’ crew centuries earlier. Nevertheless, much of Planet Ocean still was a new frontier stretching where humans had never looked. The naming of about four new marine species daily testifies that, while twentieth-century explorers may be less blind to unknown ocean life than in the past, they still lack 20:20 vision.
Scientists often cruise separately to locations of their choosing, bringing knowledge together in hindsight rather than in planning. This scattered approach has created an incomplete “photo album” of Planet Ocean with many snapshots, but also many gaps. Scientists realize that merging datasets would produce a better “photo album” or even a “film” of all marine life. Mark Twain classified “lies, damned lies, and statistics,” but experience has taught scientists that only censuses, numbers, and statistics measure whether Planet Ocean is changing, for better or worse.

The more transparent ocean

As scientists sample more completely, with better nets, remotely operated vehicles (ROVs), roaming autonomous underwater vehicles (AUVs), and manned submersibles (Figure 3.1), the ocean is becoming more transparent. Precision sampling of the water layers and seafloor now rivals what we can do on land. Exploring the sea, of course, costs more because sailing a research ship costs more than driving a pickup truck.

With sound waves from acoustic instruments, scientists count organisms from afar (Figure 4.1) and map bumps and mountains on the seafloor. Sensors mounted on AUVs “sniff out” chemical signatures from distant hydrothermal vents. Electronic tags on animals tell us where they are and measure their environment, before sending data to shore or
satellites. Via the Internet we can follow albatrosses as they leave their feeding grounds in Alaska for their romantic Caribbean mating rendezvous. Electronic tags can reveal whether “Tirion” the tuna (with apologies to J.R.R. Tolkien) is dining near Tokyo or San Francisco this month.

New molecular tools solve taxonomic problems. Although one microbial cell may be indistinguishable from the next under highest magnification, a “genetic microscope” can differentiate the agent of lethal paralytic shellfish poisoning from a tasty mussel appetizer. Ann Bucklin, a leader of CMarZ said, “We used to think we knew many species well, but the advent of DNA barcoding has radically altered that perception”.

We’ve come a long way since Captain James Cook mapped the ocean with only a sextant, sun, and stars to tell him where he was, and dropped a long line weighted with lead and a little cup to measure depth and composition of the seafloor. GIS, Geographic Information System, has catalyzed new mapping techniques that show exactly where organisms live in the ocean, a first step is learning why they live there. Multibeam acoustics and echosounders tell us the depth and composition of the seafloor. Census researchers used mapping and other tools to follow migrating animals as they move through the ocean and to link individuals...
and species to their environment. Census researchers even named turtles and invited the public to follow migrating individuals from day to day.

**Living ocean: diversity, distribution, and abundance**

The Census observed diversity, distribution, and abundance of ocean life. Although studies typically focus on just one of these attributes, the gears overlap. For longer than a century, fishermen and scientists alike collected ocean life with nets ([Figure 3.1](#)). They lowered bottles over the rail to collect small volumes of water and their microbes. They designed bottles early in the twentieth century and modified them in the 1960s with sterile plastic and Teflon coatings to avoid contamination. When declining catches and increasing curiosity drove fishermen and scientists into deeper water and more difficult habitats, they improved simple bags and scoops dating from ancient Greece.

Nets and bottle samplers collect some organisms well from some waters. Bottle samplers, however, collect small volumes appropriate only for enumerating small, but concentrated, organisms like microbes. Towed nets damage fragile jellyfish and comb jellies as they wash to the bottom of the net. Only specialized nets that sample large volumes catch rare animals. Sampling life in specific environments like coral heads or hydrothermal vents must target small areas with special tools.
The *Multiple Opening/Closing Net and Environmental Sensing System* (MOCNESS) was developed in the 1980s and modified for CMarZ to catch small, rare organisms. Its stacked nets open and close at specific depths, sampling a narrow depth range. CMarZ scientists deployed a 10 meter by 10 meter version with fine mesh to capture small organisms. They sampled tens of thousands of cubic meters of water and collected rare deep-sea life, providing the first live observations of some. The mouth of the MOCNESS was fitted with a high definition video camera and a *Video Plankton Recorder*. The recorder photographs the water entering the net to compare images of live animals entering to damaged ones caught in the net.

Cameras sample the seafloor too. For many decades, bait has attracted deep-sea life in front of cameras, but they quickly eat the bait. Cameras tell us little about how different species respond as day changes to night and seasons change. Release of new bait packages at programmed intervals reveals arrival times and attracts a broader array of life.

Grabbing and coring devices evolved from simple beginnings early in the twentieth century to ones that slowly penetrate seafloor sediment without blowing away the tiny animals and microbes at the sediment surface. For decades the devices have collected sediments and their life,
and recently the Census studies of continental margins (COMARGE) and abyssal plains (CeDAMar) used them widely.

Because corers cannot penetrate hard bottoms, Census scientists in the Mid-Atlantic Ridge (MAR-ECO) project sampled as fishermen do, trawling rugged bottoms with dredges and fortified nets. Trawling, however, misses many epifaunal organisms that live on or attached to the seafloor, and mobile organisms that sense and avoid approaching nets. These shortcomings inspired new submersible tools, towed cameras, ROVs, and AUVs (Figure 3.1).

Early on, Fred Grassle advocated submersibles such as ALVIN to study the oceans ALVIN carries three people into the deep sea and became famous for discovering both hydrothermal vents and the Titanic. Grassle recognized the value of first-hand observations that place organisms in the context where they were collected. Leading the first biological expedition to hydrothermal vents in 1979, Grassle needed tools to precisely locate and sample patchy habitats. Vent fields span just a few square kilometers or less of seafloor, and single vent openings are less than a square meter. Because vent organisms require specific habitats within these small areas, sampling even a few centimeters from a vent alters which species are found.
Again and again, scientists have had to adapt to sample the deep sea.

The high cost and scarcity of manned submersibles led to the development of unmanned ROVs. Operators watching live video feed relayed through a fibre-optic tether guide the ROV across the seafloor below. Sitting on the ship, they manipulate mechanical hands to collect samples and to deploy and recover experiments. The newest innovation is untethered AUVs programmed to follow a planned path. At the end of a “mission,” scientists retrieve the AUV, remove stored data and recharge the batteries for another excursion.

Submersibles, ROVs, and AUVs collected samples at precise locations for the Census’ Chemosynthetic Ecosystems (ChEss) project. The Census of Seamounts (CenSeam) needed similar tools to sample seamount ecosystems quantitatively and without destroying them. ChEss developed AUV tools to track chemical signatures to hydrothermal vent openings and then photograph them on a precise grid. With these tools, scientists have located and mapped black smoker vents and also more diffuse vents, which are trickier to find. Vent temperatures as hot as 407 °C, which melt plastic and damage lenses, make imprecise navigation fatal to expensive equipment.

Specialists working with delicate gelatinous zooplankton recognized that such technologies as scuba diving in shallow water and undersea
vehicles in deep water could let human eyes peek at underwater life in situ. Census scientists in Japan developed a small ROV system that dives to 1,000 meters depth from small vessels and brings back environmental data and high-quality video of zooplankton.

**Ocean imagery**

The spectacle of ocean life has inspired artists for millennia. In this tradition, Jacques Perrin and Jacques Cluzaud of Galatée Films partnered with the Census to film *Oceans*. The Census jumped at the opportunity to showcase ocean life to a broad audience. As noted by Jesse Ausubel, “Marine ecology must succeed both as an applied science and like astronomy as a source of wonder and humility. I firmly support an alliance between art and science”. For four years, Census scientists from around the world collaborated with the Galatée team while they filmed 200 species at more than 50 locations globally.

The Galatée team captured the beauty, speed, fragility, and strength of ocean life with new technologies. In rough seas, stabilized cameras removed vibration, and an electric mini-helicopter approached and filmed animals quietly. A towed torpedo camera moved with animals swimming as fast as 15 knots, and a camera on a pole over the side of vessels filmed others swimming at 8 knots. Collectively, these techniques showed...
animals moving in ways not previously seen. For the public, the result was a spectacular film. For science, the Galatée team created a scientific legacy of more than 400 hours of images of organisms moving in their natural habitats.

**Listening to the ocean**

Acoustic sensors send out sound waves that bounce off objects and show their outlines. Acoustics now map topography and sediment type that defines seafloor habitat and species. Some acoustic tools can map seafloor biota such as coral or clam beds, and thus guide sampling. After acoustic surveys, sampling can target particular regions and extrapolate the results more broadly for management applications.

Acoustics measure abundance of ocean life, one of three main objectives of the Census. Gas-filled swim bladders in fish control their buoyancy and thus their depth without wasting valuable energy swimming. Swim bladders also reflect sound waves in a distinctive way so individual fish can be counted without lowering a net into the water. The reflected sound helps managers decide how many fish remain and how many can be caught before a fishery becomes unsustainable. Formerly the managers depended heavily on historical trends of catch by fishermen, which is more extensive, but less reliable, than scientific trawl
and acoustic surveys. Improving fishing technology can counter declining
trends in catch, so populations may appear stable or even growing when
the opposite is true. Scientific trawling surveys can correct for changing
fishing effort, but they are expensive and slow.

Until recently, acoustic surveys also proceeded slowly and estimated
abundances in small spans of ocean. But acoustic echosounders now
widely and swiftly survey a 100 square-kilometer swath of seabed bigger
than Manhattan in less than a minute. Scientists used this technology off
New Jersey and then on Georges Bank and counted approximately 250
million fish (50,000 tons) in one large school, probably herring, without
taking any from the ocean or harming them (Figure 4.1). Although
different species may reflect sound in similar, indistinguishable ways
when one species dominates, acoustics are groundbreaking for censusing
marine life with no fixed address.

Acoustics also provided submarine communication for the Census.
Hydrophones count salmon migrating past underwater listening stations
along the Pacific coast of North America and acoustic tags follow diving
mammals in the Antarctic and elsewhere (Figure 4.2). Acoustics allow us
to see the oceans as animals do.
Where animals move, rest, feed, and reproduce

The variability of Planet Ocean determines who lives where, and when and why they move. Distribution of marine life, along with diversity and abundance, inspired the Census. Fish and mammals move hundreds or even thousands of kilometers in pursuit of mates, food, suitable temperatures, or oxygen. All burn energy and risk death by predation and starvation.

Species that breathe air at the surface often dive to dine. Seals and whales dive from the surface where they breathe down hundreds or even thousands of meters to find prey with whistling and sonar. Fish, crustaceans, and other invertebrates hide in the dark deep where predators can’t see them, but then surface at night to feed. For fishes and invertebrates, these vertical migrations create a dawn and dusk “rush hour,” where predators and prey commute to and from their preferred deep locations to rest or dine safely near the surface at night. Some move up from 500–1,000 meter daytime depths, rising higher than elevators carry humans in the tallest skyscrapers. The octopus *Stauroteuthis syrtensis* lives near the bottom, but has been collected 1,690 meters above the seafloor.
Horizontal migrations often follow familiar, short routes. Blue crabs travel only a few kilometers, moving from the coastal ocean into estuaries to spawn. At the other extreme, whales, turtles, and seabirds swim or fly thousands of kilometers from areas to feed and grow to other locations where they mate and give birth. The juvenile and adolescent turtles that hatch in the western Pacific, but swim to California to feed, almost matching the long migrations of bluefin tuna. Turtles can’t match the swimming speeds of Olympic champions like Michael Phelps, but they swim farther. Still, bluefin tuna racing faster than 90 kilometers per hour wallop the 7 kilometers per hour that won Phelps a gold medal in Beijing.

The movements of many species have been known in general terms for more than a century. Captains on whaling ships knew where to locate their targets at different times of year from ship observations around the world. For decades, scientists attached small tags to fish, offering rewards for returning and reporting their location. Some tags were returned, but what about those that are never seen again and where had the returned tags traveled before they were found?

Like other technology, tagging has recently progressed by leaps and bounds. Passive Integrated Transponder (PIT) tags emit radio frequencies akin to those attached to merchandise in stores to foil shoplifters or track inventory. When signaled, a tag responds without harming the fish.
Unfortunately, the fish must pass within tens of centimeters of the receiving scanner. Nonetheless, for decades PIT tag technology has counted salmon swimming across river dams, an ideal application because they funnel through a narrow fish ladder.

Since the late 1950s, scientists have implanted acoustic tags in fish that signal receivers as fish swim past. Their acoustic signals extend hundreds of meters, a limited range, but farther than the radio signals of PIT tags. The pencil eraser size and 2–3 year battery are further improvements.

The Pacific Ocean Shelf Tracking (POST) project of the Census arrayed “listening curtains” of hydrophones at strategic places to identify tagged fishes as they passed. The arrays were designed to survive storms and trawlers. The proportion of tagged salmon and sturgeon that returned to spawn, swimming past curtains at pinch points at the mouths of rivers or between Vancouver Island and the mainland, revealed survival rates. Fish passing each array showed the movement of multiple species of salmon, green sturgeon, and sixgill shark. Knowing their movement helps us know their growth and age at reproduction. Although these approaches requiring listening curtains help little in tracking migration in the open ocean where no land masses create bottlenecks, they are powerful tools for identifying and tracking anadromous fish that migrate from the ocean into rivers to spawn.
**Animal ocean view**

The “monkeycam” mounted on a monkey’s back reveals an amusing “monkey view” of the world on David Letterman’s television show. Since the 1960s, marine biologists mounted similar cameras on animals for serious “biologging” of the environment wherever the animal swims or dives. The earliest depth recorders attached to seals timed impressive diving feats. For example, Northern elephant seals routinely dive down to 600 meters and occasionally to 1,550 meters. Since then, miniaturized, more reliable biologgers have increased the range of sensors and the migrations that they track. Satellites now communicate with the animal’s sensors from great distances.

The *Tagging of Pacific Predators* (TOPP) project refined tags to measure temperature, light, depth, and salinity around animals and refined other tags to sense their pulse and temperature. Biologging now brings together behavior, physiology, and oceanography to show how an animal experiences its environment. Sensors that measure temperature, salinity, and depth are attached to seabirds, fishes, and marine mammals (Figure 4.2). Light and pressure sensors on tags estimate chlorophyll, and thus phytoplankton abundance. From light and depth, new algorithms calculate longitude, while latitude is estimated from the timing of sunrise and sunset.
Specialized tags have specialized uses. Archival tags that inertly accompany animals and write an electronic diary can track species like elephant seals or shearwaters that return to colonies where their tags can be recovered. For real-time tracking, TOPP developed GPS tags that relay observations and exact position to satellites. Because diving animals at depth cannot communicate with satellites while they are in deep water, tags on whales and seals broadcast as animals surface to breathe. When Penelope, the elephant seal, swims 14,400 kilometers over a 7 month period, for example, we know exactly where she is and much about her experiences. And even late-night television viewers have been following the travels of “Stelephant Colbert”, an elephant seal named for American satirical news host Stephen Colbert.

For animals that breathe oxygen in water, and do not surface to breathe as marine mammals must, new “popup” tags store data and then detach from the animal and float to the surface to relay data through satellites back to land. These tags, which don’t have to be retrieved, collect and then transmit biological and environmental data from sharks and tuna.

Biologging innovations come fast, promising to see the ocean as animals do. For many years, the conductivity–temperature–depth (CTD) sensors lowered over the sides of ships have precisely measured salinity, temperature, and depth. Now attached to animals, biologgers explore
ocean fronts and sea ice formation for us. TOPP developed biologging
technology to map the physical ocean to find migration “highways” and
biological hot spots where animals congregate. While improving
biologging knowledge, it also guides management. Interviewed on *The
Today Show*, a US morning news program, TOPP co-leader Barbara
Block explained, “This is a wild ocean…we have an opportunity in our
lifetime to work in this ocean to protect it.”

Because even miniaturized archival tags are still too bulky to attach to
small animals such as young salmon, they mostly track marine mammals,
large fishes, and birds. But the first computers filled large rooms and did
far less than the Blackberries and iPods that fit in our hands today.
Someday, small tags will move with small fish and even smaller ocean
life.

Today, tags reckon location from day length and the timing of sunset,
but too imprecisely for complex coasts where precise location is critical.
Researchers working in northern Europe inserted archival tags in fish, but
learned that in seas with midnight summer sun, the tags could not
calculate location! Until new technologies and miniaturization resolve
these limits to knowledge, radio tags will remain the technology of choice
in small animals and in small, complex coastal regions.
Making the most of what we already measure

Mistaken identity confuses the analysis of measurements already on the books. Species that look alike despite vital biological differences demand tools to distinguish them. The Census has embraced two emerging molecular technologies, barcoding and pyrosequencing, that push back this limit to knowledge. The Marine Barcode of Life (MarBOL), has collaborated with Census projects to identify species using barcodes that differ a lot between species, but little if at all within a species.

Project CMarZ built a seagoing assembly line to establish barcodes of all 7,000 currently known zooplankton species. Taxonomists remove individual specimens from the net, identify them, and then barcode them in a shipboard molecular lab. Much like an automobile assembly line, this efficient marine assembly line ensures samples are fresh and links a unique barcode to an established name based on morphology. CMarZ, like ICoMM, the International Census of Marine Microbes, has also begun “environmental barcoding” of bulk samples without sorting individuals. Mixing biodiversity in a blender speeds processing and skips tedious microscope work. Although the blend cannot accurately tell us abundances of species, the presence or absence of known barcodes does show presence or absence of species. Already DNA sensors detect toxic algal blooms and specific larvae of invertebrate bivalves. Although COI
barcoding cannot discriminate among microbes unless they have mitochondria, sequencing that determines the order of the nucleotides that compose DNA and RNA found in the other parts of the cell forms the core tool for ICoMM. Pyrosequencing uses chemoluminescence of the nucleotide sequences of other targets such as short loops of ribosomal RNA particularly well. Pyrosequencing identifies microbes from bacteria to archaear to protists. The integration of reference DNA barcodes for multicellular organisms and some microbes and RNA loops in many microbes can populate genetic “libraries” that can be paired with classic taxonomy to make the most of what we have already measured.

Census projects have made consistent methodologies a cornerstone of their large and intercomparable datasets to build on previous broad-scale comparisons of drifting plankton or seafloor benthos. The Census of Coral Reef Ecosystems project (CReefs) developed tools to compare reefs. The Autonomous Reef Monitoring Structure (ARMS) is a stack of standard plates that mimic reefs. They deploy the “reef condos” around the world and, after some time, recover them to find who and how many have moved in, providing a standardized comparison of colonizers. Because some organisms avoid ARMS, they sample incompletely, but they show relative diversity without methodological complications.
Other Census projects have compared existing standard methods at multiple locations. The *Natural Geography in Shore Areas* (NaGISA) project sampled transects in exactly the same way to produce a standardized global dataset on life from shores out to about 20 meters depth. NaGISA wrote a methodology guide for intertidal studies, and the *Arctic Ocean Diversity* (ArcOD) project also wrote one for ice researchers. For deep-sea sampling, the *Census of Diversity of Abyssal Marine Life* (CeDAMar) wrote on methods to ensure comparability of samples.

Census scientists contributed to standard checklists of species for seamount fishes, Chinese ocean biota, Gulf of Mexico biodiversity, and Japanese zooplankton, and field guides for Californian and global Hydrozoans. They also produced regional guides to fauna and flora, as well as keys to identify squat lobster. CMarZ scientist Vijayalakshmi Nair, a retired scientist in India, brought retired taxonomists back to their microscopes, linking their expertise to barcodes, ensuring that their classic knowledge of species would link to barcode data. Together, these strategies shared data, even between generations of experts, and thus standardized protocols for valid comparisons.
Sharing fosters collaboration

The Census deposits all its data in OBIS to share with everyone via the World Wide Web. Census projects have developed other databases and analytical tools, many linked to OBIS. OBIS verifies its entries with its partner, the World Register of Marine Species (WoRMS), which is compiling an authoritative global list of all marine species names. By October 2010, viewers can find 25 million data records at www.iobis.org (Figure 4.3). Each record identifies geographic position, depth, collection date, source, and verified species name of each specimen. Analysts can overlay global distributions of species and diversity mapped on environmental drivers like water temperature or salinity.

The 17 projects within the Census pull together massive datasets, some brand new and some assembled from sources scattered around the world. Merging the datasets and then displaying them with new visualization tools in novel ways evokes fresh, intuitive understanding. The Mapping and Visualization team of the Census coordinated with the Education and Outreach group and Census projects to develop a Census highlight layer, now included within the Google Earth application (Figure 4.4). New databases spread before audiences a new view on maritime boundaries, human impacts, and biogeographical provinces. Collaborating with the
National Geographic Society, the Mapping and Visualization team is drawing and distributing a wall map that will include Census activities and discoveries (see Figure 1.4).

Analysis of the frequent positions of TOPP’s tagged animals demonstrates how to make the most of what we already have despite imperfect observations. Models of the FMAP project analyze observations over time to locate an animal, despite uncertainties about positions. The models weight each position to filter out unlikely locations and weight closer locations more heavily than unreasonable ones. For example, grey seals don’t leap unreasonably around the ocean, thus their migration can be inferred more precisely by filtering out locations that imply great leaps. A second model infers complex behaviors along migration routes. Leatherback turtles migrating in the North Atlantic slow down at night to feed or navigate cautiously. Differentiating between an animal migrating and stopping to dine tells analysts where animals are and why during their long migrations. These models pinpoint subtle environmental cues that replace signposts in the open ocean.

Pivotal thresholds or reference points in population numbers tell biologists how many individuals of a species can be fished without spiraling the population toward collapse. An underexploited fishery sheds
jobs and leaves nations hungry. Overexploited populations recover slowly, if at all. But better statistical estimates of these reference points are now possible, including how many fish are present and how much fishing a population can endure.

For over a century ecologists have compared ecosystems with *species-area curves* to show how quickly new species are found with wider sampling, and more recently to evaluate species loss. FMAP proposed that finding species more slowly as sampling of coral reefs widened showed fishing impact. Because unseen species can mislead, this approach must be used with caution.

Statistical tools predict broad pattern from limited data. In measurements on the shelf, they can find key thresholds where temperature, depth, or bottom substrate limits the distributions of species. Thresholds, often in easily measured variables, tell where species are likely to be found. For example, depth, temperature, and carbonate predict where deep-water corals live on seamounts.

Great auks, Steller sea cows, and Caribbean monk seals were visibly hunted to extinction, but statistical tools may help us know when less visible species have been lost. One study suggested that of 133 candidate marine species, only 21 were globally extinct rather than regionally eliminated. Extinctions included three marine mammals, five marine
birds, three marine fishes, five marine mollusks, three corals/anemones, and two types of algal species. Although many consider broadly distributed ocean species less vulnerable than their terrestrial and freshwater counterparts, this assumption is sometimes incorrect because marine extinctions are harder to see.

Once a species is no longer seen we may think it has gone extinct, but wider searching and new methods may rediscover it later. Fishermen off South Africa caught the famous coelacanth, once thought extinct. How far a search must be extended to find a species can tell us if its habitat is shrinking or lost. Species that occur in a specific habitat and are sampled irregularly make this approach difficult. Incomplete sampling of a site in different seasons or sampling during natural environmental fluctuations can exaggerate depletion or obscure extinction. In short, good biological data are needed to infer extinction, and shortcuts are few.

Statistical tools can show novel evolutionary relationships. With vector analysis of many barcode data, CMarZ diagrammed similarity among zooplankton taxa. Because the diagrams resemble geometrical paintings by the twentieth-century Swiss painter Paul Klee, they are called “Klee diagrams.” The diagrams can be viewed at a range of resolutions “zooming in” on a specific region like a single genus to compare species relationships (Figure 4.5).
ICoMM inferred evolutionary relationships in living microbes from the clues of persistent fossilized lipids that persist in sediments. This emerging approach promises new knowledge of how microbes are related, a difficult problem in a group with few morphological features.

The Census has invented, adapted, and embraced these tools to extract a new view of the living ocean and its diversity, distribution, and abundance. Beginning around the ocean rim, exploration of Planet Ocean continues.
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Coral reefs, rocky shorelines, and muddy bottoms add to the potentially millions of species in the ocean, but the range of habitats (Figure 5.1) from spectacular, species-rich coral reefs to species-poor intertidal pools adds them unevenly. Exploration of the ocean began easily with flipping over rocks on the seashore to see what hid beneath or snorkeling on a reef teeming with colorful fishes. But this strategy explores only a portion of the intersection of sea and humanity, missing many areas that support commercial fisheries and myriad ocean life.

Three field projects of the Census focused specifically on the coastal environment. TheNatural Geography in Shore Areas, NaGISA, inventoried and monitored biodiversity in a narrow depth band of less than 20 meters wide around the world. They emphasized areas covered by macroalgae, or kelps and seaweeds, in rocky intertidal and subtidal environments and seagrass-covered, soft-bottom areas. The Census of Coral Reefs project, CReefs, brought together knowledge on coral-reef biodiversity and added new standardized approaches to taxonomy and field sampling that reduce the unknowns. Importantly, they developed a
new blueprint for assessment of coral reef diversity for science and management applications. The Gulf of Maine Area project, GoMA, is the only Census project focused on managing a specific ecosystem – the Gulf of Maine. They showed how to integrate biodiversity knowledge in ecosystem-based management of ocean life. The Future of Marine Animal Populations (FMAP) and History of Marine Animal Populations (HMAP) intersect with these environments, but deal with the changing ocean that Chapter 9 analyzes. Other Census projects cross the ocean rim, but are dealt with in other chapters.

Along the shoreline

NaGISA focused on intertidal and shallow subtidal environments because their three-dimensional structure contributes to diversity more than adjacent sediments. The characteristics and species within these habitats vary from one region to another, but they span the poles to the tropics and are ideal for global-scale comparison.

To create their global dataset, NaGISA developed standardized sampling protocols for rocky intertidal and seagrass environments (Figure 5.2). Then, engaging school children, local residents, and scientists, NaGISA spanned 245 locations, sampling some repeatedly and thus establishing long-term monitoring locations. NaGISA initiated monitoring
beyond coral reefs. The 80% decline in coral reefs may change adjacent rocky intertidal and subtidal life too, because some of their species are shared.

International workshops compiled taxonomic guides for macroalgae and key invertebrate groups, contributing to new taxonomic guides on echinoderms, hermit crabs, and seagrasses. NaGISA standardized taxonomy to ensure consistent names to a degree rarely achieved. Though a few previous studies used standard methodologies across a span of latitudes and others addressed inconsistent sampling, uniform global datasets remain rare and valuable.

NaGISA delivered to OBIS 37,000 records of specimens of 2,500 different taxa. These records include discoveries of species as small as inconspicuous crustaceans and as big as the highly visible 3 meter long “golden V” kelp *Aureophycus aleuticus* from Alaska’s Aleutian Islands (Figure 1.5c). NaGISA specimens also extend geographic ranges for previously known species along the coastal rim. Scientists learned that along the Argentinean shore, the invasive brown algae, *Undaria pinnatifida*, replaces native algae and attracts its own set of species during the winter. After an inactive winter, an offshore bank off Maine becomes a hot spot of abundant krill crustaceans that feed whales and seabirds.
Regional knowledge

Within individual countries, NaGISA studies built on established programs and knowledge. The European Union’s Marine Biodiversity and Ecosystem Functioning (MarBEF) is bringing together data on the well-studied European Atlantic. The Census’ NaGISA adds broad-scale analysis of a standardized dataset that is only beginning, but early discoveries include higher abundances of individuals of rare species in more variable rocky shoreline areas. Within the Caribbean, the coordinated sampling effort has shown a general diversity decrease from west to east. In the northwest Atlantic each region has its characteristics and patterns. Oceanographic discontinuities and breaking waves define rocky intertidal regions along the Pacific coast of North America.

Even strong Japanese science has not fully explored nearshore diversity in the western Pacific. The adjacent coral triangle region of the southwestern Pacific near Indonesia, Malaysia, and the Philippines is a hot spot of diversity awaiting exploration that spills over into the Japanese species pool.

In some NaGISA study areas, data are few or absent, such as the islands of India where three-quarters of the fauna is unknown. The approximately 12,000 species that live where the Indian and Atlantic Oceans meet
represent 6% of all known marine coastal species, but other areas of
African shorelines lack South Africa’s scientific capacity and taxonomic
emphasis, leaving marine life to be explored.

The southern hemisphere ocean is generally poorly sampled. For
example, 540 new taxa have been described just from Brazilian seagrass
beds and scientists recently discovered 50 new species in the fjords of
southern Chile. Marine life in the southern hemisphere awaits discovery.

**Break points**

Because salinity, nutrients, seafloor composition, and water temperature
often gently transition from one ecoregion to the next, so do suites of
faunas and floras. Transition regions are hot spots of elevated diversity. In
the Gulf of Maine, oceanographic conditions and tidal exposure define the
habitats for over 800 species of invertebrates. Steep-sided Cashes Ledge
in the Gulf of Maine, a feature that protrudes above the seabed into
shallow depths, creates another species hot spot that may resemble
historical rocky subtidal ecosystems in the Gulf.

Sharp changes of water masses also create diversity hot spots. The flora
along the African coastline abruptly changes from tropical Indian Ocean
species to *temperate*, or middle-latitude, species just south of the
Mozambique border. The subtropical Kuroshio and subpolar Oyashio
currents create a major faunal break on the coastline of Japan. The high
biomass, large individuals, and low biodiversity fauna in the cool,
nutrient-rich southbound Oyashio breaks sharply to the high biodiversity,
but low biomass in the warm, northward-flowing Kuroshio. From east to
west along the Alaskan Aleutian Archipelago, *Nereocystis luetkeana* gives
way to a primary canopy-forming kelp, *Eualaria fistulosa*.

Break points, such as the Wallace line that separates Asia and Australia,
define the edges of ecoregions. Regional hot spots of diversity are found
where many species share a relatively short stretch of coastline. Along the
coast, a single sample may contain few species, but moving a short way
adds more. If we do not know where and why these breaks and hot spots
exist, we will assess biodiversity inaccurately.

**From south to north**

Latitudinal patterns of biodiversity along a coast likely resemble the
familiar pattern on land where diversity in the tropics is high, but declines
toward the poles. Oceanic mass and capacity to absorb and hold heat are
great, dampening temperature differences compared to those on land, but
similar latitudinal patterns occur in the ocean likely because of other
factors.
Amid long-established declining diversity along Atlantic coasts at higher latitude, exploration has only recently filled in the details of hot spots like Cobscook Bay at the Canada-United States Atlantic border. Along the Chilean coast, invertebrate diversity decreases from 18 to 40–45° South, before increasing again farther south, likely because sub-Antarctic fauna contribute to the species pool.

FMAP built on this work by analyzing multiple datasets. Moving north or south from the great coral diversity hot spot between Malaysia and Papua New Guinea, coral diversity declines. Among the few coral species in the Atlantic the pattern is similar, but less striking. Mangroves and seagrasses exhibit similar patterns, except with seagrass, diversity hot spots occur at 30° to the north and south of the equator. Pinniped seals, sea lions, and walruses are outliers that are most diverse at the poles, and the diversity of coastal cephalopods declines both north and south from a mid-latitude hot spot in the western Pacific. In summary, no “one size fits all” for latitudinal patterns of biodiversity. Although these patterns reflect evolutionary histories, a Census study of oceanic predators affirms key roles for temperature and oxygen, and their new analysis also adds chlorophyll, a measure of phytoplankton abundance, for some coastal groups. Despite less sampling of the southern hemisphere, the patterns typically mirror those in the north.
Other data support a latitudinal pattern. The better known Antarctic macroalgal diversity declines from 62 to 68° South, and Arctic nearshore environments are less diverse than temperate areas. The catastrophic effects of glaciation during a mere blink for evolution some 10–15,000 years ago complicate Arctic patterns.

**Ocean “rainforests”**

The rich array of invertebrates and colorful fishes on coral reefs (Figure 5.3) signal species-rich environments. The coral requirements for clear, shallow waters and water temperatures above 20 °C limit them to less than 0.1% of Earth’s surface and less than 0.2% of ocean area. But their complex, three-dimensional structure packs many species in a small area and contributes much to global biodiversity. Reef-building corals themselves number less than 1,000 species, but small invertebrates hiding cryptically in the cracks and crevices of living and dead coral comprise much of reef diversity. Marine ecologists believe that coral reefs support more species per unit area than any marine habitat; indeed more than one-third of all known marine species live on coral reefs. Only the vast deep sea rivals coral reefs in species, but more sparsely and over a much larger area.

Insert Figure 5.3 here
Reef areas seem few and shallow, so it is surprising that estimates of species number are so tentative in a seemingly accessible environment. But many reefs lie along the coasts of developing nations with limited science infrastructure, or in remote places like mid-Pacific islands thousands of kilometers from any major seaport or airport, so many are poorly sampled. Finally, because the bulk of their diversity is hidden within the cracks and crevices of corals, it is difficult to sample and count.

How to census reef diversity? Beginning in 2005, the CReefs project developed a strategy to advance with every sample collected and slowly reduce the imprecision. Their strategy takes two approaches: genetic tools and standardized sampling for broad-scale comparisons.

Genetics and barcoding coral-reef life highlights the strengths and weaknesses of these approaches and how they improve diversity estimates. Barcoding the COI gene does not work for corals or some crustaceans. When CReefs sampled the central Pacific Reefs of the Northern Line Islands the species were so poorly known that there was not a single match in GenBank, the global “phonebook” of known genetic sequences. This is like searching a well-illustrated field guide and finding none of the species you’ve collected. Because many reef species are unknown, CReefs proposes naming unknown ones by their barcodes, perhaps until taxonomists write traditional morphological descriptions to
match the barcode names. CReefs has embraced the strategy of building
up that “phonebook” because barcoding works quite well for many types
of reef organisms.

CReefs holy grail of identifying diversity of coral reefs applies mass
sequencing “environmental genomics” that ICoMM developed for
microbes to multicellular organisms. While the “biodiversity in a blender”
appeals, its adaptation to multicellular organisms remains a challenge that
will take time and effort to resolve. Some multicellular organisms produce
compounds that interfere with DNA amplification, a key step in mass
sequencing. Multicellular organisms vary in size and thus contain very
different amounts of DNA per individual. The genetic signal from one
large crab could swamp the signal from many hundreds of small
crustaceans and mask the abundance of different species. Determining
presence versus absence will be much easier than assessing abundance.
Finally, because some DNA primers needed to determine genetic
sequences don’t work well in some groups of organisms, sequencing
requires multiple primers. The “magic blender” will remain a potential
technology until these problems are resolved.

To compare coral reefs, CReefs developed two standard sampling
protocols to address the challenge of collecting representative samples,
eliminating the problem that reef divers typically collect samples with
different efficiencies and scope. First, CReefs collected similarly sized heads of dead *Pocillopora* coral to capture the cryptic life inside dead corals. Second, because this first strategy misses organisms that reside within live corals and other species, CReefs developed Autonomous Reef Monitoring Structures (ARMS) modified from an earlier design (Figure 5.2). A series of PVC plates with spacers create an artificial structure on which reef organisms can settle and grow. These “reef condos” are anchored to different reefs and then retrieved after a set period of time to show what has moved in. Just as polling the residents of a Miami Beach condominium doesn’t give a full picture of all residents of Miami, the reef condos target only those individuals that like this particular habitat. But ARMS expedite comparisons of reefs anywhere in the world, and some data suggest ARMS represent overall reef diversity. Clearly, a full assessment of life on reefs will also require divers and video to assess large and mobile organisms because “reef condos” and *Pocillopora* heads assess only organisms small enough to move in. And molecular tools specialize in differentiating similar-looking species. To capture the diversity of coral-reef sediments and other reef environments, scientists must develop other standard protocols.

With these new tools CReefs took intriguing glimpses into the unknown diversity of coral reefs. They collected near Tahiti and four other reefs within a 1,000 kilometer span of the isolated Northern Line Islands. They
examined 22 small dead *Pocillopora* heads and found 403 usable

sequences from crustaceans. They discovered 135 potential crustacean

species. Rarity was the rule; 44% of all the crustaceans were sampled just

once, a pattern CReefs also found in areas such as Australia. Just 22 coral

heads contained about 30% as many *brachyuran* (true) crabs as ever

found in the most thoroughly sampled region of the global ocean, the

European seas. Cruises and shore-based expeditions discovered about 100

new species from Hawaii and another 500 from Australia alone, with

many more expected from sampling the Central Pacific. Like many

projects, CReefs conducted workshops on molecular analyses and

sampling protocols and submitted more than 400,000 data records to

OBIS.

The public, and scientists too, have paid less attention to coral reefs

than to their terrestrial counterparts, tropical rain forests. Like rain forests,
coral reefs are seriously threatened. Studies on coral reefs have focused on
corals and fishes rather than the full array of reef diversity. This

discrepancy may reflect the challenges of measuring reef diversity.
Conservationists believe that the 60% of reefs degraded or gone are taking

a significant chunk of their estimated 35% of global marine biodiversity

with them. The loss of these reefs has other costs because the economic

value of reefs is estimated at 30 billion US dollars annually. By the year
2000, humans had settled near more than 75% of the global reefs, a 25% increase since 1950.

Warming temperatures, increased pollution, ocean \textit{acidification} (more acidic oceans caused by additional carbon dioxide), and overfishing all change food webs and stress reefs globally. These stresses cause \textit{coral bleaching} that drives out photosynthetic cells that live within their tissue, eventually leaving bleached, dead coral. As the loss of corals eliminates many species that rely on them, the coral community typically begins to resemble a rocky shoreline community. Kelps and seaweeds replace the coral, creating habitats for other species, but creating a different and less-diverse community.

Surprisingly and contrary to earlier evidence of impacts on fishes and corals, CReefs found that humans did not diminish crustacean diversity in the Northern Line Islands. These remote reefs are relatively pristine compared to many reefs near humans, and moderately impacted reefs sustain high levels of biodiversity compared to the species losses on severely impacted reefs like many in the Caribbean, where many invertebrates are declining.

The most comprehensive dataset ever assembled on reef fishes shows that the productivity of reefs grows with biodiversity of fishes, making the most diverse reefs the most productive ones. This illustrates \textit{functional}
redundancy in ecology, where more diverse environments may withstand disturbance because multiple species fill similar key roles in food webs and other functions. A species that plays the same ecological role as another insures against the loss of one. These comprehensive data suggest not that diverse reefs are invulnerable, but rather that diversity helps mitigate the pervasive human footprint on reefs.

Cooler waters in the Gulf of Maine

The Gulf of Maine from Cape Cod north to the Nova Scotian shelf and Bay of Fundy provides a cooler ocean world. The Census project GoMA chose this relatively well-sampled and less diverse waters to make existing information accessible for ecosystem-based management.

Though the beaches and rocky coast of Maine and Atlantic Canada may seem pristine, humans have been there for 6,000 to 8,500 years. Early hunter-gatherers had little impact, but evidence from archaeological middens, or ancient garbage dumps, shows changed food webs, including cod, 3,500 years ago. European colonization in the 1700s transformed parts of the environment by loading nutrients, altering seabed habitat, and overfishing. Europeans significantly reduced cod on the Scotian shelf by 1859 and overexploited most vertebrates. They hunted three species of mammals and six species of birds to extinction. In the early 1900s,
mechanized and more-efficient fishing technologies depleted coastal and
Georges Bank cod. By 2007, cod landings in the Gulf of Maine system
fell to 5–6% of their 1861 levels. Multiple effects cascaded through the
ecosystem. Fishing still affects the Gulf of Maine ecosystem despite new
restrictions that recognize the importance of habitat, vulnerable species,
and biodiversity.

Against this backdrop in the Gulf of Maine, GoMA assembled
biodiversity knowns and unknowns, and set a research strategy. They
designed a system for available information, supported field efforts in key
areas, and moved biodiversity knowledge into ecosystem-based
management.

Over four decades, fish surveys by US and Canadian fisheries agencies
created a goldmine of knowledge about the Gulf of Maine. GoMA
analyses show that fish diversity is lowest on the shelf and in basins
around the Gulf of Maine and highest on Georges Bank and on the upper
continental slope. Because fishes associate with specific types of seabed
habitat managers may be able to extrapolate where Gulf of Maine
biodiversity hot spots are likely. This is just the sort of information needed
for ecosystem-based management.

GoMA helped develop the concept of a discovery corridor, to colocate
biodiversity research where it is needed and most productive. The
discovery corridor in the Gulf of Maine extends in a triangle that fans out
from the intertidal region of the Canada–US border across the continental
shelf and to the base of the continental slope. This triangle encompasses a
variety of habitats from the rocky shoreline to areas that contain the
greatest known regional abundances of deep-water corals, such as sea
Genetic analyses suggest species of coral and other invertebrates
previously unknown from Canadian waters and potentially new. Because
scientists know little about the deep water of the discovery corridor and
adjacent seamounts, GoMA assembled experts to gather available data
and plan geographic and taxonomic strategies to tackle the unknowns.

In the Gulf of Maine, like elsewhere, scientists know the least about
microbes which likely add the greatest diversity. Some 696 known species
of phytoplankton, plus many unknown microbes, need study. GoMA
microbial experts extrapolated upwards from estimated microbial
abundance and analysis of abundant taxa to estimate as many as 10,000
types of phytoplankton and 400,000 types of bacterioplankton.
Bacterioplankton in the Gulf represent about 20% of the known global
diversity total, hinting that the microbial diversity in the Gulf of Maine
may be especially rich. High-throughput analysis offers the potential for
monitoring microbes as harbingers of ecosystem health in the Gulf of
Maine and elsewhere.
A GoMA project illustrates the human bias in how we view, sample, and even manage the ocean. **Figure 5.4** compares size of adult stages of different species and reinforces the common-sense view that the smaller the organism, the less we know. Whales and fishes are almost fully known, invertebrates are partly, but unevenly, known, and microbes are almost totally unknown. To illustrate these points, the cycling of food and nutrients in the Gulf of Maine and elsewhere is driven largely by microbes within a “**microbial loop**,” yet many are unknown. Compare lists of known species from the Gulf of Maine to well-known European waters and assume proportions of phyla are similar. The conclusion: small creatures from nematodes to small crustaceans are scarcely sampled and thousands of invertebrates species are unknown. Cruises over the last decade already discovered many new species, including cryptic forms that are virtually impossible to distinguish based on morphology alone.

GoMA discovered schools of herring over 40 kilometers wide move into shallow water. Large-scale acoustic imaging shows that schools of this key commercial species form and disperse in minutes to hours. The herring move quickly from the sides of Georges Bank as they form spawning shoals at the top of the bank near sunset. A disorganized mass of herring assemble into a highly organized school that follows a few
leaders. As the fish assemble, they stir a convergence wave in the water that propagates outward at 10–20 kilometers per hour. In about 40 minutes, hundreds of millions of fish across tens of kilometers of ocean synchronize. Imagine assembling and moving the entire human population of the United States in synchrony in 40 minutes!

The US National Marine Sanctuaries include Stellwagen Bank, a 2,100 square-kilometer area on the southwest corner of the Gulf of Maine that has been fished more than 400 years. Most activities are permitted on the Bank, as in most parts of 200 protected areas in the Gulf of Maine. Like the discovery corridor, it attracts researchers studying fishes to plankton to seabirds and marine mammals, using varied tools. For example, the towed HabCam camera makes automated species identifications, and when paired with broader-scale maps adds useful information for managers. These different types of information work in statistical analyses such as random forests models adapted to the sea. These analyses now determine how gradients in temperature, seafloor composition, and other environmental characters affect benthic species in the Gulf of Maine and elsewhere. This approach points to physical variables measured easily over broad areas as “surrogate” predictors of species, communities, and biodiversity patterns.
The incorporation of biodiversity knowledge into decision-making increasingly guides ecosystem-based management and related management that integrate diverse information. Biodiversity and marine habitat mapping may be incorporated into ecosystem-based management from scales of genes to ecoregions. Because much-needed information is unknown, even for familiar regions like the Gulf of Maine, scientists must assemble and stretch the known into multiple applications. With much known about many species in many ecosystems, particularly those targeted by fisheries, bringing that knowledge together is a knowable next step.

The *Gulf of Maine Register of Marine Species* lists known species in the Gulf of Maine, including species thought to occur based on knowledge from adjacent regions. Once completed, this list will link to the *Encyclopedia of Life*, OBIS, and elsewhere. In November 2009, the Register listed 3,141 species, about a third were verified. An additional 821 species from various datasets and habitats increase their provisional list to 3,962 species.

New knowledge offers an opportunity to manage coastal environments better. Linking knowledge along the shoreline through regions, hot spots, and break points from north to south, will make management more productive. Exploration of the broad array of coastal life from warm coral
reefs to the cool waters of Gulf of Maine and beyond (Figure 5.5) will collectively propel ecosystem-based management for more sustainable ocean use.

Insert Figure 5.5 here
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At the ends of the Earth

Although a sphere has no ends, remote Arctic and Antarctic Oceans seem like the ends of the Earth for most of us. Few locations conjure up exploration as the poles do. Freezing in the dark, Amundsen, Peary, Scott, and Shackleton raced to “conquer” the poles first. Only five decades ago Byrd established permanent Antarctic bases. Ice and darkness invoke mystique and challenge. As much as I might grumble, bobbing seasick in the drizzle, fog, and gales off Newfoundland, my discomfort pales next to ArcOD (Arctic Ocean Diversity) scientists loading rifles to fend off polar bears that kill with one swipe of a paw. Rifles and every single piece of equipment must be flown or shipped in advance. There is no running to the hardware store for replacement parts, and sailing and flying people and equipment to deserted poles drains budgets. Polar researchers still routinely drag equipment across the ice on sleds just as Norwegian explorer Fridtjof Nansen did a century ago as he collected some of the first data on Arctic ice movement. Snow machines have replaced dogs, but much is the same.

Our glimpses are longer during 24 hour summer sunlight, when protective ice cover retreats and we can see ocean life, but the water and
seafloor beneath permanent ice are rarely sampled. New glimpses of spectacular life “through the ice” by Census scientists have been featured in postage stamps, art exhibitions, and worldwide press coverage (Figure 6.1).

Despite few humans reaching the poles, human effects are apparent. Global warming imperils polar marine life, as captured in photographs of polar bears on melting ice floes. Shortly after scientists first described them, hunters extinguished Steller’s sea cow (*Hydrodamalis gigas*) and great auk (*Pinguinus impennis*), leaving only dusty museum specimens to prove they existed. The Arctic ice cover that hinders scientific access also protects areas from fishers and hunters. If melting opens the Arctic to shipping, exploration, and fishing, marine life will change. Antarctic exploitation hunted fur and elephant seals to extinction, and diminished global populations of blue, fin, humpback, southern right, and sei whales, some by half and some by 99%. The collapse of fisheries in accessible seas in the 1960s drove bottom trawlers to more remote areas. As bottom habitat was simultaneously destroyed, stocks of Antarctic marbled rock cod, *Notothenia rossii*, and mackerel ice fish, *Champsocephalus gunnari*, quickly declined.
A tale of two oceans

The 19 Arctic ecoregions and 21 Antarctic ecoregions comprise just 17% of the total 232 global ecoregions. Nevertheless, the ice and darkness overwhelming their annual cycles singles them out, encompassing habitats from the intertidal to the deep sea, and pelagic environments in between (Figure 6.2). Land surrounds the ice-covered Arctic Ocean, whereas the Southern Ocean surrounds the ice-covered Antarctic land (Figure 6.2 inset). Both have summers of continuous light, winters of continuous darkness, and major habitat defined by ice. Scattered stations of various nations created hot spots of ecological knowledge, some going back hundreds of years. In the Antarctic, different nations run 45 seasonal or year-round stations leaving wide gaps of knowledge in between.

The knowledge gaps made Arctic and Antarctic research projects an absolute must for the Census, and in 2007 the International Polar Year focused public interest and opened opportunities for collaboration. Because the ArcOD and Census of Antarctic Marine Life (CAML) projects spanned remote habitats, they encouraged collaboration within and outside the Census. Although not rich in species, polar life is attuned to cold, seasonal light, and ice, and their cascading effects. Distinct
species have evolved to live in Arctic and Antarctic waters, but some live
at both poles.

The Arctic Ocean occupies only 4% of the global ocean, smaller than
the 23% of the Atlantic and 46% of the Pacific Oceans. At 6% the
Southern Ocean is just slightly larger. The land surrounding the Arctic
Ocean creates some of the widest continental shelf in the world. More
than half of the Arctic Ocean is less than 200 meters deep, and the modest
Arctic Ocean holds 31% of all continental shelf habitat. The Antarctic
shelf raises the total polar shelf by 11.4% to 42%. Freshwater flowing
from Canada and Russia into the Arctic Ocean creates distinct
environments, strongly affected by season, circulation, and *stratification*
of water. This layering of fresh and salt water limits nutrient availability
and therefore Arctic productivity. Freshwater melting off the land into the
Southern Ocean is less important to ocean life.

The deep water of the Southern Ocean separates the Antarctic shelf
from shelves around other continents, isolating Antarctic ocean life. But
satellites show that the Antarctic Convergence where the cold Antarctic
Circumpolar Current and warm northern waters meet may breach the
isolation. Circulation gyres move algae, zooplankton, and even larval
stages across this boundary, leaving temperature rather than any
hydrographic barrier to isolate Antarctic life.
The polar past

When the Bering Strait opened up about five million years ago, Pacific species moved in and mixed with Arctic species. The narrow Bering Strait between Alaska and Russia connects the Arctic Ocean to the Pacific and the Fram Strait between Greenland and Norway’s Spitsbergen Island connects the Atlantic to the Arctic. Species from the Atlantic cross the Fram Strait, adding to a mix of deep-sea cosmopolitan species and endemic species that evolved in the Arctic. Over eons, circulation, geology, and glaciation opened and closed connections, and endemic species evolved when connections closed. ArcOD scientists are assembling a biogeographic history of the Arctic that links these events to today’s biota and helps predict tomorrow’s ocean.

Molecular tools help reveal evolutionary history. The “molecular clock,” concept dating to the early 1960s assumes molecular change is proportional to time and dates evolutionary events from evidence of genetic sequences. The molecular clock helps differentiate migrants from species that evolved separately in the polar oceans. Different lineages evolved between the shallow Antarctic and sub-Antarctic regions about five million years ago, from the urchin Sterechinus, to the brittle star Astrotoma agassizii, to the bivalve Limatula, to the limpet Nacella. Over eons, species evolved in the Antarctic and spread northward into deep
water, through *tropic submergence*. The deep Southern Ocean may have
pumped out diverse crustaceans and anemones. Thirty million years ago,
some deep-sea octopods evolved from a common Antarctic ancestor and
moved north (*Figure 6.3*), as have isopod crustaceans. The Antarctic
amphipod crustacean genus *Liljeborgia* has eyes, but related species that
have moved into the lightless deep sea are blind. During long evolutionary
periods, some isopods without eyes “emerged” from the deep sea into
shallow water, through *polar emergence*. The development of 29 lineages
of sea slug, *Doris kerguelensis*, with Antarctic ancestry hints that the
“discontinuity” of the Antarctic Convergence may be less critical than
once thought.

Fauna in shallow Antarctic water differs from that on the adjacent slope
and abyssal plain, and across the Antarctic Convergence. How did this
diverse fauna evolve? Many Antarctic species evolved when glaciers
interrupted the continental shelf and grounded ice broke the shelf into
isolated “bays,” where species evolved separately by *allopatric* speciation.
But the present shelf is more or less continuous and species intermingle so
that diverse octopus, isopod crustaceans, and sea cucumbers coexist.
The icy waters of polar present

In the polar present, ice that covers the entire Arctic Ocean during winter retreats by half during summer. As winter’s perpetual darkness gives way to summer’s perpetual light, temperatures warm and diatoms dominate algae in the ice, contributing as much as half the primary productivity in the central Arctic. Ice and snow still block out all but a few percent of any light that might penetrate to water beneath. Nevertheless, the little light passing through during springtime melting energizes the *sympagic* community living at the ice–water interface (Figure 6.4) and within salty brine channels that permeate the ice. Feast follows winter famine as the algae multiply and invertebrates colonize and feed in this unique world where water in brine channels may be three times saltier than seawater and thus remain fluid at $-10^\circ\text{C}$ without freezing.

Although the extreme conditions in ice are too much for most life, those species that can cope enjoy an “all you can eat” buffet of algae on the underside of the ice using the available dim light (Figure 6.4). Low diversity, but high abundances, of protists and meiofauna, as well as larval stages of benthic species, live and feed on algae in the rich matrix. Different species, some endemic, can live in the dynamic, three-dimensional ice, including newly discovered predators. Fecal pellets from
the feeding frenzy sink and feed other species. Arctic cod eat amphipods and other ice invertebrates, and they, in turn, feed seals and other species in the food web. Buckling ice heaves up ridges that extend more than 20 meters below, adding complexity. CAML also found important effects of ice melt on Antarctic plankton, though they studied ice melt dynamics less than ArcOD.

In early Arctic July, warming melts and breaks up ice, thus releasing algae. The movable feast then transfers to the water column. As sea ice and algae fluctuate, so does faunal abundance and diversity. By summer’s peak, the endless days deliver more light to Arctic waters than reaches sunny Caribbean beaches. But light still limits because the angle of the sun is low, and soon nutrients become depleted and so productivity is brief.

While food is abundant, the response is rapid. Just as bears on land store fat for winter hibernation, the zooplankton in the sea store “food” in lipids, then respond quickly when new food arrives with the spring bloom. Growth rates in zooplankton are strongly seasonal, and many species eat whatever they can get. Both growth and depth distribution of zooplankton fluctuate seasonally, altering energy transfer between surface and deeper layers. The daily vertical zooplankton commutes common in many different ecosystems (see Chapter 7) stop during 24 hour Arctic sunlight.
In feeding season, abundant seabirds, seals, and whales such as bowhead, gray, and beluga congregate at oceanographic fronts where water masses meet. They feast in numbers that rival those anywhere on Earth. In the Arctic the feast spans a few dominant copepod species, such as *Calanus finmarchicus*, to capelin, *Mallotus villosus*, and herring, *Clupea harengus*, and on to whales, seals, and seabirds. Euphausiids, or krill, fill a key part of this role in the Antarctic.

Scientists know the dominant phytoplankton and zooplankton that fuel the Arctic biota. Much species data, however, were scattered in file cabinets in Russia, the United States, Canada, and Europe. When ArcOD convened five years ago, only some 300 species of zooplankton and 300 species of phytoplankton were known. ArcOD planned how to fill gaps by focusing on poorly known regions and groups of organisms, which now fill published papers and new taxonomic guides in development.

In summer, glaciers cover only 20% of the shelf around the central Antarctic land mass, but in winter extend to 60%, doubling the size of the Antarctic continent and extending beyond the continental shelf over the deep ocean. An ample nutrient supply does not make a productive Southern Ocean because iron limits phytoplankton production, except where islands naturally inject iron. Commercial companies have proposed
iron fertilization, adding iron to bloom phytoplankton, in the Southern Ocean so they take up more atmospheric carbon dioxide.

Scientists know the simple links of phytoplankton to zooplankton to fish, whales, seals, seabirds, and seafloor detritus feeders. But now they know that nutrient and energy cycling through microbes in the microbial loop helps sustain the food web in the absence of abundant phytoplankton.

The convergence between the Antarctic Circumpolar Current and northerly waters divides pelagic species between north and south. CAML refined this pattern by finding varied plankton and fishes that differ in diversity and abundance within the Circumpolar Current. Smaller zooplankton have begun to replace the euphausiid krill (Euphausia superba) that is a widespread, important crustacean in the Antarctic pelagic food web, but has declined significantly. CAML also discovered that Antarctic fishes called myctophids, or lanternfish, transfer energy from 100 meters to 1,000 meters in their daily commutes.

The polar present seafloor

Sand and gravel cover the inner Arctic shelves while mud covers the deep seafloor. After ice retreats, the feast moves to the seafloor because slow metabolism in cold water limits how quickly zooplankton can respond to the rapid spring bloom. The high biomass on some shelf seafloor,
dominated by dense brittle stars, amphipod crustaceans, polychaete worms, and mollusks, fades downward so that deep-sea communities are numerically sparse, dominated by *deposit feeders* that strip food material from ingested sediment particles. The scarce, but fresh, food that reaches the seafloor links seafloor abundance to planktonic production. Because 90% of known species live on the seafloor, it is something of a hot spot for Arctic diversity.

The Antarctic continental shelf averages 450 meters deep and sometimes extends out beyond 1,000 meters. As in the Arctic, glacial rock, gravel, and mud formed from silica shells of sinking diatoms cover the seafloor (*Figure 6.4*). A rich diversity of bryozoans, sponges, and amphipods lives on the shelf, but some mollusks, isopod and decapod crustaceans, and fishes are absent despite presence in fossils. Some groups of Antarctic mollusks and crustaceans are well known, whereas nematodes are not. Although past estimates of 80% probably inflate the level of Antarctic endemism, new reports of half or more in some groups are probably more realistic.

Along the Antarctic shelf, macrofauna encompasses one large ecoregion, some stretches are productive and rich in species, where others are sparse. Areas previously, or recently, scoured by icebergs or
perpetually beneath ice typically have low abundances and diversity because of limited food.

A plethora of new ocean life

The 60 (and counting) new Arctic species that ArcOD has discovered span from microscopic to megafaunal animals of a size seen easily in bottom photos, in habitats from ice channels through the water column to the seafloor (Figure 6.4). They found new species in little-known regions such as the Canada Basin, and in novel habitats such as the area of reduced flow above the seafloor called the benthic boundary layer. Discoveries spanned a predatory hydrozoan from brine channels, poorly studied jellyfish, and yet to be described copepod, amphipod, and ostracod crustaceans from the water column. CAML sampling increased the number of Antarctic gelatinous zooplankton species by a factor of two to three times. ArcOD also found viruses thriving in all sorts of Arctic environments.

On the seafloor, ArcOD found new species of snails, polychaetes, worms, copepod crustaceans, and sea cucumbers. They found new species of bryozoans, which are coral-like animals with calcium carbonate skeletons. Many other new species were discovered and await formal
naming. The Chukchi Sea added over 300 species to a 2001 inventory, including 21 polychaete worm species previously unknown in the Arctic.

The collaboration between the Census CAML and CeDAMar projects collected 1,400 species in the deep Antarctic including perhaps 700 that are new. A group of protist *komokiaceans*, a type of foraminifera first formally described in 1977, were unknown from the region until the Antarctic cruises collected 50 species, 35 new. The 674 or 87% new isopod crustaceans among Census collections added 15% to the global total for that group. The Census also discovered new species of glass sponges, carnivorous sponges, and calcareous sponges. They found many *epibionts*, where one species provides habitat for others and thus adds diversity. For example, the spines of one sea urchin housed 156 different species and the blades of Arctic kelp housed a mixture of attached *epibionts*.

Exploration and environmental change have expanded the known ranges of even familiar groups such as fishes. Harbingers of the consequence of warming, walleye pollock, *Theragra chalcogramma*, were found 200 kilometers further north in the Arctic and surveys sighted rare toothed whales closer to Antarctica than ever seen. Workers in the Canada Basin provided new data on marine mammals and birds. Others resolved
taxonomy problems in coral-like bryozoans and jellyfish. Not surprisingly, extensive sampling collected the largest numbers.

**Pooling polar knowledge**

Antarctic programs that had brought researchers together expedited CAML’s 2005 launch. The *Scientific Committee on Antarctic Research*, SCAR, has coordinated international Antarctic research for almost 50 years, and helped CAML hit the ground running. They coordinated research efforts and created a biodiversity database (SCAR-MarBIN) linked to OBIS. From 2007 to 2009, 34 nations and 321 scientists on 18 vessels sailed on International Polar Year and CAML cruises, an impressive effort in vessels that cost many tens of thousands of US dollars daily to operate. As of May 2009, the database contained over one million records of 8,000 species from 122 datasets. This doubles the numbers from 1993.

As of August 2009, ArcOD had delivered 26 Arctic datasets to OBIS, including 150,000 data records and was expected to surpass 250,000 by the end of 2010. ArcOD contributed to a field manual for sampling ice environments, and has worked with Russia’s Zoological Institute in St Petersburg to initiate a set of taxonomic guides for Arctic marine life that is just now beginning to appear.
Using barcoding technologies adapted from ICoMM, ArcOD and CAML discovered 1,500 species of Arctic bacteria and 700 species of Archaea. They barcoded 300 species of Arctic benthos, 93 species of fishes, and 41 species of Arctic zooplankton in collaboration with CMarZ. CAML has added over 11,000 Antarctic barcode sequences from their collections. In one study CAML examined over 25,000 plankton barcodes, where 13,000 were new sequences.

Over a century ago Captain James Clark Ross proposed *bipolar species* that live in both poles. Some species, such as the sooty shearwater, live at both poles because they migrate between. Searching their databases ArcOD and CAML found 230 species names common to both poles. Truly bipolar species don’t include cosmopolitan species that occur elsewhere, often in cold, deep water, or species that look the same and share a name, but are genetically distinct.

An international team of taxonomists identified 227 species in 12 phyla as potentially bipolar. Other studies added another 102. A strategy of assembling known distributions and a strict definition of polar eliminated 211 of the 329, and reliability eliminated 44 more. This only left 74 species living at both poles, but only 17 not found in between. Thus, truly bipolar species are rare, encompassing only five percent of a list of the most promising candidates. Although these few are currently considered
bipolar, some may eventually be found in the poorly sampled deep sea.

Genetic analysis mostly found genetic differences and cryptic forms rather than bipolar species. Thus, bipolar species that live at the opposite poles, but nowhere else, are few.

The Arctic is considered species poorer than the Antarctic for geological reasons, and bacterial comparisons support this view. A new survey of biodiversity knowledge for Canada’s Atlantic, Pacific, and Arctic waters found Arctic microbial diversity highest, but this pattern may reflect more intense Arctic sampling. Warmer water and habitat diversity enhance Antarctic biodiversity. Nevertheless, the current total of about 8,200 Antarctic versus 6,000 Arctic multicellular species, or metazoans, shows a modest difference between the poles.

The polar future

What’s left to find? An exploration of Arctic marine biodiversity led by the European Union found over 1,400 species from a 50 square-kilometer area less than 280 meters deep. Species accumulation curves show that mollusks are almost fully described, but other groups – particularly smaller-sized organisms – are poorly known. ArcOD estimates an eventual discovery of 45,000 types of bacteria, 5,000 types of archaea, and 4,500 species of protists. Arctic microbes, once thought inactive, may
not be and archaea, bacteria, and protists thrive in all types of Arctic

habitat.

The Antarctic intertidal, once thought species poor, may instead be
diverse and productive. The shelf seafloor alone may have 17,000
macrofaunal species, and that doesn’t even include the spectacular deep-
ocean diversity sampled by CeDAMar. The 90% of the region deeper than
1,000 meters also holds many unknowns!

Explorers know little about the deep basins that extend thousands of
kilometers across the Arctic seafloor. What they do know shows key
differences between species composition and abundance between sides
and tops of ridges. The newly discovered abundant hydrothermal vent
sites on the Gakkel Ridge and geologically “recent” and explosive
volcanic activity illustrate the new environments and species
yet to be discovered in remote parts of the Arctic. Unexplored areas of the
Antarctic continental shelf covered by floating ice hold other new
discoveries, as do the Amundsen and Western Weddell Sea.

**The human stain**

Warming temperatures and thinning ice add to concern about Arctic
summer multi-year ice that is declining by 2–9% per decade. These
changes might drive endemic Arctic species extinct, while others might
escape northward from warmer waters farther south, perhaps actually
increasing Arctic diversity, even as ice-dependent species go extinct. The
few long-term studies of Arctic intertidal fauna, zooplankton, and benthos
indicate a constant species pool, but changing abundance of dominant
species. With the arrival of new species and the warming of waters,
sorting out Arctic change will be difficult. Continued sampling will be
critical. Pacific seafloor species have recently appeared in the Chuckchi,
perhaps in climate-linked invasions. If seabirds that feed on plankton and
fish starve as food disappear, oceanic changes will affect the land.

Some of the most rapid warming on Earth has occurred in areas of the
Antarctic. In recent decades, surface waters have warmed by 1 °C, sea-ice
formation is 10% less, and ice shelves have collapsed, causing major
changes on the Antarctic Peninsula. Ocean acidification is expected to hit
the Antarctic first, because a wide range of organisms that use calcium
carbonate may be seriously affected by the year 2100.

Arctic exploration and oil development are rapidly expanding. The
mercury concentrations in whales that reflect their feeding is already an
environmental and health issue. If predictions of an ice-free Arctic in the
summer months by 2030 or 2100 come true, shipping traffic, oil
exploration, and fishing activity will escalate. To understand how these
activities might affect Arctic marine life, ArcOD advocated the expansion
of several time-series sampling programs in sensitive regions in the
Chukchi and Barents Sea where change is happening quickly. New Arctic
observatories could monitor changes in real time and from afar.

After whaling ships plied the water and pushed marine mammals and
seabirds to near extinction, their impacts on the Antarctic have decreased.
Fisheries for krill, toothfishes, and icefish continue to land hundreds of
thousands of tons, and krill removal has caused concern. But a central
regulatory body for Antarctic fisheries is working to ensure that food
webs are not significantly altered by these removals, though illegal
fisheries are difficult to control in such a remote area. The double-edged
sword of tourism has, on the one hand, heightened public awareness of the
Antarctic ecosystem, but on the other hand increased from 7,000 visitors
in 1992 to 35,000 in 2007, raising concerns about possible disturbances.

CAML argues that “Antarctic waters may be the best-protected marine
areas on Earth” in large part because they are shared by multiple nations
and despite their remoteness benefit from the public view of their pristine
condition. Nations claiming parts of the Antarctic for their economic
potential focus research on their claim areas. South American and
European nations focus on the West Antarctic and the Scotia and Weddell
Seas, whereas Australian, New Zealand, and Asian nations focus on East
Antarctic. Russia and the United States operate in both areas.
Bioprospecting, climate-change effects on ecosystem functions, and biodiversity loss point to a need for long-term observations similar to those conducted by the Census. Collectively they could become a Southern Ocean Observation System to signal changes in sensitive areas like the Antarctic convergence and the Antarctic deep sea.
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Chapter 7

Ocean life in motion

Many species of marine life – from microbes to whales – live their entire lives drifting or swimming, and may never see the seafloor or land. Sampling these nomads challenges the few scientists exploring the immensity of the ocean’s more than 99% of the Earth’s biosphere, and countless interconnected habitats. Much of the oceanic volume is far from shore and reaches depths without sunlight and with crushing pressure (Figure 7.1). Differences in temperature, salinity, pressure (depth), light, and oxygen and hence food determine where ocean life lives and why (Figure 7.2). Organisms move continuously in this fluid world – some drifting with the currents and others swimming in seasonal migrations over thousands of kilometers. Others migrate vertically more than a kilometer in a single day. For an organism only a few centimeters in length, this is not a commute, but a daily marathon.

Insert Figure 7.1 here

Insert Figure 7.2 here
Ocean life mostly travels to feed or reproduce. Their poetry of motion spans gentle pulsing of jellyfish or the powerful strokes of tuna and whales swimming across thousands of kilometers of blue ocean. But we don’t know where they go, how they go, or why they go. Their movement complicates learning their diversity, distribution, and abundance. We will never sample the immense ocean completely. Nevertheless, new tools refined during the last decade helped us understand life in motion, demonstrating untold diversity of drifting microbes, blue highways in the ocean, oceanic globetrotters, and predator hot spots.

**Small is big**

Their small size ([Figure 7.3](#)) belies the importance of marine microbes. They make half the food that fuels all life on Earth, and they control the global nitrogen, sulfur, iron, and manganese cycles. Without microbes, life on Earth would end. A single liter of seawater contains more than 100,000,000 individual microbes and a modern study is doing well to collect genetic sequences for more than 0.01% of them. One study estimated 20,000 microbial forms (OTUs) in that liter of seawater. More recently, archaea alone were estimated at 3,000 OTUs per liter. Molecular tools applied to protists project species richness comparable to the archaea. Microbes are the least known and physiologically most complex forms of life on Earth.
Mind-boggling microbial diversity makes it difficult to count. Counting a few dominant types in a sample is easy, but many rare forms complicate the job. At the rate of 20,000 types of microbes in one liter, the 1.35 trillion-billion liters in the ocean could hold unfathomable numbers. Many rare species were first found in hydrothermal vent fluid, but rare is now known to be common. In other words, rare microbes dominate microbial communities, and only a few species are abundant.

Beginning in 2004, the International Census of Marine Microbes (ICoMM) collected more than 1,200 samples spread among all major oceans, representing 583 bacterial, 120 archaeal, and 59 eukaryotic datasets and more than 25 million sequences. Importantly, because genetic tools are used to characterize microbial samples, the term “sequences” is the microbial vernacular for “count” and thus approximates the numbers of individuals sampled. Given the size and complexity of this dataset, ICoMM is only just beginning its analysis, but early findings are intriguing. They estimate approximately 10,000,000,000,000,000,000,000,000,000 (or $10^{29}$) total bacteria in the global ocean. Collectively microbes are up to 90% of total ocean biomass, and the remaining minority includes all the invertebrates, fish, and whales in the sea! There are differences among the bacteria, archaea, and protists.
that make up the microbial world; in some areas archaea are as abundant
as bacteria, but only 10% as diverse, and protist diversity is similar to the
archaea.

How rare is rare? In other words, if a sample has many rare “species,”
does this mean that there are lots of rare forms that occur everywhere in
low numbers (“everything is everywhere”) or are rare forms just that?
Different depths and seasons in the Arctic show similar biogeography of
rare and common forms. It is possible sequencing picks up only the
commonest of the rare or, more intriguingly, that rare forms live
everywhere. Are rare species active or are they marginal, dormant forms
that do very little? An analogy might be a stray tropical fish swept up to
Nova Scotia in the Gulf Stream, but destined to die quickly. It is thus
more a biogeographic footnote than ecologically important. Some rare
species in the South Pacific are metabolically active in nutrient and other
cycles, and rare species at hydrothermal vents bloom when environmental
conditions are good.

As expected from past studies and in their global survey, ICoMM found
the most abundant type of life on Earth, the Alphaproteobacteria, which
cycle carbon, nitrogen, and sulfur, represent half of microbial abundance
and 25% of microbial biomass. Alphaproteobacteria are everywhere.
The blue-green bacteria (Cyanobacteria) of the genera *Prochlorococcus* and *Synechococcus* are the most numerous bacteria in the ocean, living at 100,000 to 1,000,000 individuals per liter of seawater. Their photosynthesis produces perhaps half the primary production in the ocean. Cyanobacteria were the first organisms to produce oxygen as a byproduct of photosynthesis and oxygenate the Earth’s atmosphere billions of years ago. We and most animals owe our existence to them. Among Archaea, the phylum Crenarchaeota, once thought to live only in extreme environments, are now known to be widespread in the ocean and may outnumber bacteria below 100 meters, where they help cycle carbon. Among eukaryotes, abundant dinoflagellates include forms that cause harmful algal blooms. But dinoflagellates are notorious for having many copies of each gene, so are overcounted in studies that enumerate numbers of sequences. Tiny eukaryotes whose diversity has only been recognized within the last 10 years are most abundant. An unclassified dinoflagellate first reported from Antarctica can number 29,000 cells per liter. This microbe also occurs in the Arctic, Pacific, and Atlantic Oceans, Framvaren Fjord in Norway, and the Black Sea, but whether it is a single cosmopolitan species or multiple forms remains unknown.

Few microbes swim and it is tempting to assume they could disperse like the scent of holiday turkey through our homes and become present everywhere. But new work suggests microbial communities stay within
discrete ocean volumes with distinct temperature and salinity called water masses (Figure 7.2). Many water masses span thousands of kilometers in distance and thousands of meters in depth. In the same water mass, bacterioplankton from an 8,000 kilometer stretch of deep water in the North Atlantic are similar over thousands of kilometers, but differ from microbes only hundreds of meters away in a separate water mass. This was true for common Proteobacteria and also for rare forms, suggesting that the rare ones did not stray in from elsewhere.

In stark contrast to this finding, in a sample of pyrosequencing analysis, the 20 most abundant Arctic and Antarctic bacterial forms were shared between poles. Although this pattern rests on just one genetic sequence, it suggests bipolar microbial species. Why are the two poles of the world similar yet adjacent water masses different? And why is bipolarity apparently common in bacteria and not in animals (see Chapter 6)?

Although microbes play well-established roles in natural cycles, within the last 5 to 10 years researchers have found novel roles for them in cycling of carbon, nitrogen, sulfur, and iron. These new roles include how they use methane and ammonium in environments without oxygen, and the discovery of archaea that use energy in ammonia to build biological molecules. These little powerhouses also play a key role in climate in that bacteria fix nitrogen gas from the atmosphere and ocean and convert it...
into a valuable nutrient for phytoplankton. Just a few types of bacteria fix nitrogen, and in laboratory experiments they react strongly to increased seawater acidity, a phenomenon already seen in the ocean. In similar experiments, seawater acidity changes metabolism and carbon uptake in *Prochlorococcus* and *Synechococcus*. If acidification continues, nitrogen and carbon cycles may change too, yet scientists scarcely know the roles and identities of key microbes.

**The time traveler’s microbe**

Biologists would dearly love to ride H.G. Well’s *Time Machine* back in time to understand why the living world is what it is today. The extraction of DNA from preserved material to reproduce living dinosaurs in Stephen Spielberg’s *Jurassic Park* is a stretch. Fossil DNA is rare and its interpretation controversial. But fat-related lipids are more robust than DNA and can persist in sediments for billions of years and help trace evolution. Though the puzzle evolves constantly and key pieces have disappeared over time, molecular analyses teach much about evolution. And much effort has gone into the lipid database. Like genetic databases, scientists around the world input data for future analyses. ICoMM began with an existing library, The Lipid Maps database (www.lipidmaps.org), which focused on biomedical applications, and broadened its scope to include marine lipids. With *MICROBIS*, the ICoMM microbial database,
genetic and lipid data are placed in a precise geographic location that opens up a range of new analyses. For example, analysis of more than 100 types of diatoms, a group of phytoplankton, showed that rhizosolenoid diatoms, evolved 91.5 million years ago, give or take 1.5 million years. Although not quite a time machine, this newly precise timing is novel, and it beats time travel and trying to elude the dinosaurs that ruled the Earth when rhizosolenoids evolved.

Lilliputian swimmers

Microbes are not the only drifters in the ocean. Small zooplankton swim and drift, although their small size and weak swimming make them planktonic (Figure 7.3). The Census of Marine Zooplankton (CMarZ) focused on zooplankton that live all of their lives in the water column, the holoplankton. Excluding the meroplankton, which are primarily larval stages of seafloor animals that spend a small portion of their life as drifting plankton, zooplankton encompass about 7,000 known species in 15 phyla. CMarZ targeted potential biodiversity hot spots throughout the world, including such remote regions as Southeast Asia, the polar oceans, and water below 5,000 meters. All these regions yielded new species to the Census, and all will yield more. CMarZ is the first global-scale synthesis of marine zooplankton to bring together all major zooplankton taxa. In every ocean basin during more than 90 CMarZ cruises since 2004,
CMarZ filtered millions of cubic meters of water at more than 12,000 locations. An additional 6,500 archived samples supplemented these collections. From them, CMarZ mapped global distributions of protistan Foraminifera and Radiolaria, and wrote a new global monograph about Hydrozoa (jellyfish). They also examined basin-scale diversity of Atlantic Ocean ostracod crustaceans, and Indian Ocean chaetognath arrow worms, and will add others.

Why all of this effort? Besides the roles zooplankton play in food webs noted in Chapter 2, they also cycle carbon, nitrogen, and other ocean elements, though differently than microbes. In particular, they export food from surface waters down to layers beneath. Although the diversity of 7,000 species of zooplankton pales by more than a million next to global marine diversity (see Chapter 3), many zooplankton are abundant and widespread species.

While zooplankton are not diverse globally they can be diverse locally. A net collection from a single oceanic location could contain hundreds of copepod crustacean species, representing 10% of their global total. Imagine a sample containing this large a proportion of global biodiversity for any other group. Because zooplankton habitat is water itself, it is less complex than three-dimensional coral reefs or the microbial and chemical complexity of sediments. The bacterial world is defined by milliliter
gradients in nutrients or oxygen, whereas swimming zooplankton 
experience a bigger world of thousands of cubic meters or less. For them, 
depth and neighbouring organisms also define habitat. Consider the deep-
sea jellyfish, *Pandea rubra*, that spends part of its life attached to a 
swimming mollusk.

Though many zooplankton are cosmopolitan or widely distributed, 
some look-alikes are genetically distinct species that require genetic 
barcoding to distinguish. As of late 2009, 2,000 of 7,000 described 
zooplankton species had already been barcoded, including protists, 
jellyfish, calanoid copepods, euphausiid krill, ostracods, pteropod 
mollusks, and chaetognath arrow worms. Barcoding revealed genetically 
distinct populations of copepods, krill, and arrow worms. CMarZ hopes to 
have all known zooplankton species barcoded by the completion of the 
first Census of Marine Life in October 2010.

These different strategies discovered 89 new species, of which 52 have 
already been formally described. These include new jellyfish from 
Norway, the Gulf of Maine, and the deep ocean, and at least 15 new 
species of ostracod crustaceans, new species of copepod, and shrimp-like 
mysid crustaceans. The Census added an additional 8% to the known 
copepods in Southeast Asian waters and 2% to the global total. In the 
open ocean CMarZ found a peak in species number at 750 meters and
fewer species at higher latitudes. *Herbivores* that feed on phytoplankton dominate the upper layers and widely distributed carnivores and detritus feeders dominate at depth. Filtering large volumes of sparsely populated deep water with large, fine-meshed nets collected rare specimens from copepod crustaceans to fishes. The Census discovered a unique and diverse fauna under Arctic sea ice that earlier studies largely missed because they sampled in summer months after ice dynamics critical to Arctic and Antarctic ocean life had finished (see Chapter 6).

Endemism is rarer in deeper dwellers than shallower species. Frequent endemism in the Arctic and Antarctic contrasts with less diversity at these high latitudes. For example, only about 4% of global holozooplankton live in the Arctic, perhaps reflecting the difficulty of adapting to cold and ice.

FMAP studied latitudinal patterns in drifting euphausiid crustaceans, foraminifera, different groups of fishes, and cephalopod mollusks. This work expands a previous FMAP study that showed a subtropical peak in diversity of billfish, tuna, and other predators that paralleled foraminiferan diversity and increased diversity in warmer water up to a point. Then it declined, perhaps because further warming reduced the solubility and thus availability of oxygen, another significant diversity predictor. Other metabolic issues, such as overheating in the warmest waters may also
come into play and explain the mid-latitude peak for oceanic animals that
contrasted the equatorial peak for many coastal organisms (see Chapter 5).

Because zooplankton indicate environmental change, CMarZ has
analyzed their patterns over decades of sampling. Since 1946, Continuous
Plankton Recorders on ships have surveyed the North Atlantic. By
passively filtering out the organisms that pass across a revolving band of
silk mesh as it is towed, this simple device has produced valuable
biological datasets on the North Atlantic and elsewhere. They show that in
the last few decades in the North Sea, warmer-water species have
displaced cold-water copepods, a critical food resource for many larval
fishes. These data have also demonstrated “regime shifts,” zooplankton
changes related to shifts in water masses in the Northwest Atlantic,
Northeast Pacific, and Northwest Pacific. Preserved samples in Japan
showed decadal oscillations of copepod diversity and abundance over 40
years. Zooplankton abundances in South Africa’s Benguela Current
actually multiplied 100-fold over previous decades, possibly reflecting
climate change. A rare 130 year plankton time series from the Black Sea
showed increased comb jellies replaced copepods and reduced anchovy
recruitment. Thus, knowledge of the ocean past has helped understand
decimating fisheries stocks and linked them to zooplankton. Researchers
also anticipate Arctic warming will change the timing and magnitude of
phytoplankton production and move more species through the Arctic.
From drifters to swimmers

Because biodiversity spans from genes to ecosystems, research can appropriately focus on single species rather than communities for some groups of organisms. With most species of large vertebrates, from fishes to whales, focusing on where they live and why is timely. On the one hand, sampling communities of microbes and zooplankton across the ocean at different times is necessary and workable. Sampling communities of whales, seabirds, and big fishes, on the other hand, is impractical and destructive, so researchers focus on observation of individuals.

Scientists have long marked organisms with tags and fluorescent particles, and photographed unique scars on whale tail flukes to learn where they move. Knowing where animals move can define populations of commercial species and locate critical habitats. Although it may improve fishing efficiency by telling fishermen where the fish move, it may also show how populations are linked and could be protected or restored. It may eventually fill in black boxes on where species move.

A tale of two zipcodes

In the Pacific Northwest of Canada and the United States, salmon is king. I am not referring to king (Chinook) salmon, but to the six species of salmon at the center of the history, culture, cuisine, economy, and politics
of that part of the world. Artists admire salmon in Haida art and tourists
buy smoked salmon as they leave Vancouver airport. Salmon research
generates interest and controversy far beyond the biologists doing the
research.

POST, the *Pacific Ocean Shelf Tracking* project, inserted small radio
tags into thousands of individuals spread over 16 species of fish and two
species of squid, and then monitored their movement and survival with a
“curtain” of listening receivers that detect them as they swim past ([Figure
7.4](#)). At first they tried to study the oceanic portion of the Pacific salmon
life cycle. Do salmon travel specific areas of the ocean the way they
follow specific rivers? Where and when do salmon die in the ocean?
Pacific salmon species are *anadromous*, swimming into freshwater rivers
and streams to spawn. They may stay there for two years before
swimming back to the ocean. Salmon abundance and mortality in
freshwater are well known, but in the larger and more open ocean,
abundance and mortality were unknowable. Consider that a given *cohort*,
or “generation,” of salmon may move (and die) anywhere within a 16,000
kilometer loop as they move from Oregon to Alaska and on to Japan over
a five-year stretch. *That* is a fisheries management nightmare!

Insert Figure 7.4 here
The rapid expansion of human development in the North Pacific in the twentieth century increased agriculture, fishing, river damming, and logging, and climate is now changing. It is hardly surprising that some Pacific salmon populations dropped below 10% of their historical levels. These declines punctuate the need to know where individuals are lost from populations. An added complication is salmon aquaculture, which has created heated controversy about how hatchery-reared and, most especially, farmed salmon interact with natural salmon populations.

POST began with a “two zipcode” theory that salmon live at one location in freshwater and another in the ocean, following earlier work that found salmon and their predators use different Pacific ocean areas seasonally. POST followed early successes with salmon by tagging squid and sturgeon.

When salmon swim past listening curtains and are detected (Figure 7.4), the information is clear, but when an individual is not detected it may be because it died, swam past the line undetected, or its tag failed or was lost. Or perhaps the individual remained between listening curtains. POST curtains deployed at narrow points in migratory routes (river entrances, inland waterways, narrow straits) reduce these ambiguities, but do not encompass all habitats within the movement range.
Less than 5% of the smolt, or migrating freshwater juveniles, of anadromous rainbow (steelhead) trout, *Oncorhynchus mykiss*, survive to adulthood, and this rate varies within the Pacific Northwest. This variability determines good and poor cohorts. POST found most individuals moved downstream daily less than 1 kilometer in smaller rivers but farther than 80 kilometers in larger rivers. Once in the ocean, populations migrated at similar speeds. Wild smolt survived migration better than hatchery-reared ones, which knew little of natural predators and suffered higher mortality soon after release.

During the 1990s, Coho salmon, *Oncorhynchus kisutch*, almost disappeared from the Strait of Georgia off the coast of British Columbia and did not recover once the fishery closed. Warmer waters reduced southern populations and increased northern ones, but little was known about coho survival in the ocean. POST’s acoustic tags showed inconsistent survival in the rivers in hatchery-reared salmon. In the ocean, mortality varied among populations as the migrating fish moved as far as 750 kilometers from their Oregon release. Survival was poor in summer, but better in September. As hatchery-released juveniles moved slowly downriver through the estuary, their physiology, behavior, and survival differed from wild populations. Coho survival was affected by season and by freshwater and marine habitats.
Dam building during the 1970s coincided with declines in chinook salmon, *Oncorhynchus tshawytscha*, in the Snake River in the northwestern United States. The Snake and Yakima Rivers flow into the Columbia River. Engineers have improved fish passages and spillways, and carried fish past impounded water. Despite high cost and improved smolt survival downriver, adult returns remained poor. Perhaps transport around the impound area reduced later survival in the coastal ocean.

POST asked, what role do the dams play?

POST tagged 4,000 hatchery salmon and tracked them through rivers into the ocean, detecting five juveniles 2,500 kilometers away in their Alaskan listening array. They found that Yakima juveniles, which pass through four lower dams, were five times more likely to survive to adulthood than Snake River juveniles, which pass through eight dams. But survival in the lower river was similar for both populations, suggesting that survival was largely determined *after* they entered the ocean.

POST worked with an expensive program that transported juveniles around the Snake River dam system on barges. The fish survived during the barge trip itself, but barging did not improve survival from the last dam to the ocean. Also the barged juveniles did not return to the river at much greater rates than those that made their own way over the dams and down the river. Even though barged juveniles arrived at the ocean sooner,
their mortality in the ocean was similar to those that made their own way in the river. Because barging did not improve survival, the dams may not be the culprits harming salmon. Some endangered Columbia and Snake River chinook and steelhead stocks downstream survive the dams in those rivers as well or better than the same species migrating from the dam-free Fraser River just to the north in British Columbia. Advocates of dam removal and related mitigations must scrutinize these experiments carefully for clues to improve survival.

White sturgeon, *Acipenser transmontanus*, as long as 6 meters and weighing more than 600 kilograms are the largest fish in freshwater in North America and in the world. Truly a freshwater Methuselah, it is a living fossil that has barely changed in over 65 million years and it can live longer than 150 years – except that most stocks in British Columbia are in trouble. Rapidly declining numbers of anadromous young that migrate to the ocean may cause the declines of 27% in Fraser River populations. To begin testing this hypothesis, POST helped tag 100 white sturgeon in the Fraser River in 2008, but results are still incomplete.

Further south, green sturgeon, *Acipenser medirostris*, is in trouble too. Anadromous, like the related white sturgeon, they spawn only in three rivers and congregate in Oregon and Washington estuaries. Though caught along the coast from Baja California to the Bering Sea, their
migration is unknown. Additional listening curtains from California to Washington augmented POST receivers, to match the sturgeon’s range.

Green sturgeon tagged north of Vancouver Island in winter migrated to rivers and estuaries in California, Oregon, and Washington in spring.

Individual fish repeatedly used specific estuaries and rivers. This information can help recover this species.

Like many other sharks, predatory sixgill sharks, \textit{Hexanchus griseus}, grow slowly and produce few offspring, which makes them vulnerable.

POST tracked 59 young adults for as long as four years and found they moved no more than a few kilometers a day. During fall and winter their north to south travel spanned only 8 kilometers, and expanded to only 120 kilometers northward in late spring and summer. Most of the sharks remained in Puget Sound. In one year, 10\% left the area, and as some individuals matured, 46\% strayed 200–350 kilometers to the north and one strayed 1,400 kilometers south. The movements of mature sixgill sharks remains unknown, but they have been caught kilometers from the coast by longline fishermen. Sixgill sharks seem to lack the wanderlust of most of the species tracked by Census tags.

Sockeye salmon, \textit{Oncorhynchus nerka}, suffer great mortality. POST singled this salmon species out as part of an interdisciplinary effort to solve a complex puzzle. In the Fraser River alone, 150 distinct
populations move 100 to 1,200 kilometers upriver. Different populations move in predictable migrations in four clusters between June and October. In some years, 50–95% of fall spawners, more than four million fish, perish during the river migration, raising questions of sustainability.

Why would fish migrate in a season when migration is tantamount to suicide? POST combined tracking with physiological measurements, particularly concentrations of reproductive hormones and the degree to which they were physiologically prepared to move into freshwater. For late-spawning sockeye salmon, preparation for reproduction is the primary factor in driving ocean migration. Elevated reproductive hormones in late spawners may trigger early migrations before the primary spring/summer spawning optimum.

The Census found that salmon that failed to reach the river to spawn were more stressed, and less prepared for freshwater, than those that succeeded. Necessary salts available in the ocean are scarce in freshwater, hence the movement from salt to freshwater challenges migrants. Indeed, this is why organisms such as echinoderms (sea stars, for example) have been unable to invade freshwater over evolutionary time. They lack the physiological capacity to cope with low salt concentrations. Fish that migrated into freshwater before their gills were modified to deal with freshwater frequently died, even when in good reproductive condition.
Triggers in the open ocean can hasten reproductive hormone development.

Reproduction drives late-season spawning sockeye migration. Elevated hormones in late-season spawners may trigger migration before the spawning optimum. If individuals become reproductively prepared too quickly, they may find themselves trying to mate before they are ready, with dire consequences. The analogy to the human species is almost irresistible!

Although some salmon die in rivers, multitudes die somewhere in the ocean. Larger acoustic arrays in deeper water and smaller tags may help to pinpoint graveyards in the ocean. Indeed, the Ocean Tracking Network, a new international research program led by Canada and spearheaded by Census scientist Ron O’Dor, will do just that.

**Blue highways and truck stops**

TOPP (*Tagging of Pacific Predators*) tagged and tracked large animals that swim far in the ocean and seabirds that fly above them. TOPP tagged mostly in the Pacific, where highly mobile species feed, reproduce, and play across the largest ocean on Earth. TOPP first assumed that several species would travel particular routes – ocean highways – to converge in ocean hot spots of abundance with favorable temperature and food. A group of about 90 scientists planned ambitious tracking of 23 predators at
the top of food chain: whales and tunas, seals and squid, seals and sea
lions, turtles and seabirds. TOPP began tagging familiar species and added
new ones as they improved technologies and methodologies. They
developed a strategy of tracking guilds, species that live in a similar way,
so they could share methods and compare animals with similar
physiologies and habitat. Tagging 4,400 animals and 23 species, TOPP
discovered truly globetrotting nomads like sooty shearwaters and stay-at-homes like female sea lions. White sharks migrated from coastal
California to a meeting place the Census dubbed the “white shark café.”
Visiting the café off the coast of Hawaii and traveling back demonstrated
strong and persistent homing behavior.

Some salmon sharks (*Lamna ditropis*) tagged in the Alaskan Arctic in
the summer strayed as far south as the subtropical North Pacific in winter
and spring. They spent the most time in water cooler than 10 °C above 50
meters, but some swam into both cold 2 °C water and warm 24 °C water.
Physiological measurements showed cardiac and other adaptations to cold
water where their fish prey abound.

Pacific bluefin tuna (*Thunnus orientalis*) and loggerhead turtles
(*Caretta caretta*) mostly swim west to east, breeding in the western
Pacific and then migrating as juveniles to the central California coast to
feed. After spawning, tuna migrate into the South Pacific, encompassing
the largest known home range among marine species. Leatherback turtles 
(Dermochelys coriacea), like loggerheads, breed on the beaches of 
Indonesia and migrate to California in late summer to feed on abundant 
jellyfish. Traveling in the opposite direction, another population of 
leatherbacks breeds on Costa Rican beaches in Central America and 
crosses the Pacific to the food-poor subtropical Pacific. But the king of 
travel is the sooty shearwater (Puffinus griseus), which travels the Pacific 
from the Antarctic to Alaska’s Bering Sea in an “endless summer” with 
abundant prey to eat and favorable habitats for breeding (Figure 7.5).

As predicted, tagged juvenile Pacific bluefin tuna swam seasonally 
from the western to the eastern Pacific region and then from Baja, 
California to Oregon and congregated in a hot spot in the California 
Current.

Animals that TOPP equipped with electronic tags revealed their hot 
spots in the North Pacific. Predators of many species, from leatherback 
and loggerhead turtles to sooty shearwaters, to whales, tunas, seals, and 
sharks, all congregate at several locations in the California Current. There, 
seasonal upwelling of nutrients creates a rich supply of food that 
nourishes abundant prey for many top predators.
If the California Current is a cluster of hot spots, what are the “blue highways” of nomadic migrations? The North Pacific Transition Zone is one major highway and a hot spot too. Along this highway east to west across the Pacific, mixing subarctic and subtropical water create a patchy, “trail of crumbs” across the ocean that is followed by tunas, seals and sea turtles, albatrosses and shearwaters. Some travel the highway, whereas for others it is a destination. Year after year, the females of two elephant seal populations that breed along a 1,200 kilometer span of the Mexican and California coastlines feed along the highway. Although the southern population must travel far, they travel it anyway. Individual white sharks repeatedly follow distinct highways to use their coastal hot spots again and again.

TOPP found out how animals divide up these highways and hot spots. Because the hot spots lie along highways we may think of them as “truck stops.” Though many share the same routes and truck stops, they often use them differently so they don’t compete. Pacific bluefin, yellowfin, and albacore tuna are related, but the endothermic bluefin tuna maintain their body temperature and can tolerate cold. Because yellowfin and albacore tuna, and mako and blue sharks lack this ability, their body temperatures drop in cold water, which confines them to tropical to mid-latitude waters. Blue whales travel 100–200 kilometers off the coast of California to feed on euphausiid krill, whereas humpbacks chase schools of small fish.
inshore. Black-footed albatrosses feed in warm productive waters, while the cooler and patchier waters to the north favor Laysan albatrosses. Animals also partition habitat vertically. Thus, bluefin feed on abundant sardine and anchovy near the surface layer, whereas albacore feed in deeper water.

Animals also avoid competing in hot spots by eating different diets. White sharks dine on marine mammals that congregate in coastal colonies, while mako sharks hunt fish on the continental shelf. Even sharks are not mindless eating machines. Salmon sharks feed on pollock and herring, but mako and blue sharks feed on squid and sardine.

Three hot spots within the California Current add seasonal separation. Tunas, blue, mako, thresher, and juvenile white sharks feed and grow in the Southern California Bight, and then tunas visit the California Marine Sanctuaries and Baja California seasonally. In short, species once thought to wander indiscriminately have well-defined “kitchens,” “bedrooms,” “hallways,” and “nurseries.”

TOPP discovered that unusual ocean conditions change the behavior in some species. In winter, sea lions usually stay close to shore, taking excursions for less than a day. When seasonal upwelling of nutrient-rich waters was delayed, however, they sought food 300–500 kilometers
offshore and changed their diet from squid and anchovy to sardine and rockfish.

Managers of endangered species, protected areas, and fisheries can use knowledge of hot spots of diversity and activity in pelagic waters of the open sea. If we know where animals are likely to be, we can plan accordingly. Others want to know what lives in the deep blue sea.
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Into the Deep

“Provehito in Altum,” the motto of my undergraduate university and current employer, translates to “Launch Forth into the Deep.” Glimpses of the dark solitude of the deep ocean create a lasting memory. Early morning in January, 1988, the research ship *Atlantis II* held position off Mexico. Another scientist and I, along with the pilot, climbed into *ALVIN*, the world’s best-known submersible. Like stuffing three people into the trunk of a Volvo, the other scientist and I shoehorned our modest frames into *ALVIN*’s sphere much more easily than the 6’5” pilot. We all avoided tea or coffee because tiny *ALVIN*’s toilet was a plastic bottle. None minded these discomforts because adventure and discovery lay ahead. As we sank to the seafloor through a thousand meters and stared out through the plate-sized portholes, light faded to total darkness interrupted only by flashes of bioluminescence from mid-water organisms. Inside, *ALVIN*’s titanium hull protected us as dimly lit safety dials showed increasing depth and crushing pressure.

At the bottom of the sea

After sinking steadily through blackness for an hour, the outside lights showed an eerie landscape of rolling hills covered by mud. During his
historic 1934 bathysphere dive to about 1,000 meters off the coast of Bermuda, explorer William Beebe described a similar lifeless plain, unaware the sediment hid a riot of species of Lilliputian life crawling around in it (Figure 8.1).

Now in 1988, *ALVIN*’s pilot radioed up to the surface, announcing we were on bottom, and requested direction and distance to find the Guaymas hydrothermal vents. As the vents appeared through the blackness I thought that the spectacular photographs and video of Guaymas and other vents can scarcely capture the eye-popping smoking chimneys and beautiful bouquets of life clustered around them.

More than six decades after Beebe’s first look into the deep sea, Census scientists dedicated five of their 14 field projects to its study. These projects focused on the continental slopes (COMARGE), chemosynthetic environments (ChEss), seamounts (CenSeam), the Mid-Atlantic Ridge (MAR-ECO), and the abyssal plains (CeDAMar). In crushing pressure and in darkness without photosynthesis, the deep sea is the largest frontier on Earth today. From the vast plains of the abyss with their sparse fauna, to the diverse continental margins with their spectacular hydrothermal vents, seeps, and rich diversity of species (Figure 8.1), the deep sea yielded myriad new knowledge for the Census. Census leaders from the
deep-sea projects worked together to summarize the importance of the deep sea, shown in Table 8.1.

The continental margins extend from the shoreline to the abyssal plains, but the continental slopes from the shelf edge to the abyssal plain form the landward portion of the deep sea (Figure 8.2). On the slopes, most food sinks from surface waters or arrives horizontally from adjacent shelves. Scientists have known about this material for decades, and that biomass and activity decrease rapidly with depth. With depth, larger organisms become less numerous, leaving bacteria and meiofauna to dominate abyssal life. But sparse abundance and biomass do not mean less diversity than in productive rainforests and coral reefs. This paradox has focused researchers on food supply to the deep sea and how it affects diversity.

When the Census deep-sea projects were developed less than a decade ago, almost 50 years had passed since Howard Sanders and Robert Hessler had killed the myth of a lifeless deep sea. They proposed that continental slope and abyssal plain sediments might rival tropical rainforests in diversity. Fred Grassle and Nancy Maciolek’s hotly debated projection of 10 million deep-sea invertebrate species provoked new
interest in the early 1990s. Nevertheless, most scientists accept that many
species live in the deep, despite its apparent uniformity that sharply
contrasts the three-dimensional structure of species-rich coral reefs.

The deep Southern Ocean has yielded a wealth of new species, from
copepod and isopod crustaceans, corals, anemones, to glass sponges. Some
species of foraminiferans are distributed over 17,000 kilometers from pole
to pole, while others change within only 1,000 kilometers. Even when
focusing on better-known groups, MAR-ECO found about 10% of the
species they sampled along the Mid-Atlantic Ridge were new, including
fishes, multiple squids, sea stars, and sea cucumbers.

The Census used new tools (see Chapter 4) and coordinated deep-sea
research around the world to show that varied habitats add to deep-sea
biodiversity, building on discoveries in the 1980s and 1990s. The Census
explored biodiversity in oxygen-minimum zones or OMZs (where
bacterial respiration, or breakdown of organic matter, depletes oxygen),
seeps, whale carcasses, and dense deep-water coral beds with abundant
fishes. They visited seamounts and manganese nodule fields on the
abyssal seafloor, novel habitats of seabed brine pools and methane pock
marks, and even mud volcanoes (Figure 8.2). As they studied the most
poorly sampled habitat of Earth, CeDAMar standardized sampling tools
and methods. With considerable data already in hand, COMARGE
worked on the slopes to standardize new sampling, train taxonomists, and
explore rich deep-sea diversity.

How do cold, pressure, and scarce food support a rich array of life?

Three patterns of diversity known for decades complicate the answer.

Diversity decreases away from the equator, biodiversity peaks at 2,000–
3,000 meter mid-slope depths depending on taxa, and zonation of multiple
species changes at key depths rather than independently of one another.

Solving the mystery of diversity in the deep will inform understanding of
patterns elsewhere on Earth, and guide ecologists and conservationists in
identifying and protecting hot spots, as on land.

Patterns related to latitude and depth

Like elsewhere in the ocean and on land, deep-sea species are more
diverse in the tropics and less diverse at the poles. The abundant
foraminiferans in deep-sea sediments, isopod crustaceans, bivalves and
gastropods, and fishes confirm this pattern. Along the Mid-Atlantic Ridge,
far from the continental margins, the diversity of zooplankton to
cephalopods and demersal fishes increases from cold Iceland towards the
warm Azores. These patterns are clearer in the northern than the lesser-
known southern hemisphere, where the pattern is questioned. Exceptions
occur, as with deep-sea nematode threadworms that appear more diverse
in productive temperate environments than tropical areas, and the debate continues.

Latitude itself does not drive these patterns, but is a proxy for energy, food, evolutionary and ecological history, and food supply that do. Temperature and salinity that create pattern in near-surface and coastal habitats (Chapters 5–7) are unlikely players because they vary little in the deep ocean, so studies have focused on productivity and basin age. In the abyss from the equator to the Southern Ocean, ongoing CeDAMar analysis will clarify whether there is a latitudinal gradient in the southern hemisphere.

Diversity generally peaks at 2,000–3,000 meters, as documented 30 years ago. However, the diversity of polychaete worms peaks at different depths in the eastern North Atlantic than their polychaete cousins in the tropical Atlantic, or compared with isopod crustaceans in the Southern Ocean. Neither megafauna on the Antarctic slope nor Mediterranean invertebrate groups peak at intermediate slope depths. Nonetheless, the pattern is reported widely. Why is this peak commonly found? Intermediate levels of available food may optimize diversity at mid-slope depths, where abundant or sparse food depress diversity in shallower and deeper environments, respectively. Nonetheless, several studies find nematode diversity increases with surface phytoplankton production, and
the pattern in mollusks and crustaceans are just the opposite, with no
intermediate peak in either group.

To understand these on-again, off-again peaks, COMARGE analyzed
16 datasets from around the world from depths of 1,000 to 4,000 meters.
Aside from some Southern Ocean taxa, they confirmed the mid-slope peak
in most regions and taxa. Many exceptions were caused by oxygen-
minimum zones that intersect slopes at intermediate depths and create
low-oxygen dead zones, where only microbes flourish. A rich terrestrial
literature suggests too little food depresses diversity, as does too much,
though some studies show a linear rather than hump-shaped relationship.
Satellites and models have mapped surface phytoplankton, a proxy for
food falling to the seafloor below that augments sparse measurements of
deep-sea food supply. Bottom currents and topography confound these
models. COMARGE found an intermediate food supply corresponded
with peak diversity over depth. Their generalization explained only a
small portion of diversity, in part because diversity was particularly
variable, and thus unpredictable, where food input was low.

At ocean scales, faunal patterns in the abyss mirror food production far
above and define biogeographic regions. Within weeks after a seasonal
phytoplankton bloom at the surface, fauna thousands of meters below
respond to the feast of falling *phytodetritus*, or decomposing
phytoplankton, jellyfish falls, and whale carcasses. Responding to decadal meteorological changes like El Niño, food production on the surface changes, and diversity, distribution, and abundance of abyssal communities change accordingly. In the abyssal Indian Ocean, protistan foraminiferans were more diverse in more productive areas. In the Mediterranean abyss, more and better food increased abundance and diversity. In the abyssal central Pacific, more food increased polychaete diversity weakly. Perhaps faunal diversity would peak at intermediate supply in the abyss, but too little food reaches the seafloor to see the full range of response.

Bottom-temperature data from the World Ocean Atlas, was the best predictor of deep-sea diversity, and adds to a long-known pattern of higher diversities in warmer climates, where increased metabolism promotes rapid speciation and thus diversity. Because the diversity of polychaete worms peaked at a boundary between water masses in the northeast Atlantic, gradients or ecotones between adjacent environments may be hot spots of deep-sea diversity.

COMARGE compared well-known zonation patterns and found that except for consistent zones along the junctions of continental shelves with upper slopes, depth zones varied among six regions, perhaps because of real geographic differences or perhaps because of sampling differences.
But depth itself does not appear to explain the regional variation, particularly in light of depth differences in zones for different taxa within a region. Because the warm surface waters of the Mediterranean Sea penetrate to greater depths than elsewhere without changing the shelf-to-slope junction noted above, temperature does not explain zones. Similarly, the cold link between polar shelf and slope waters fails to explain the zonal patterns. Because the environment becomes more uniform with depth, zones span greater depth in deeper water. Nevertheless, fauna change sharply at 400–500 meters and at 1,500–2,500 meters.

In the Gulf of Mexico, food affects depth zones, but on the Mid-Atlantic Ridge, zonation was absent. The scarce food on and near the Mid-Atlantic Ridge may link pelagic and demersal fishes more closely than those on continental margins, and eliminate seafloor zonation. CenSeam found species and coral assemblages on seamounts were strongly linked with depth, but seamount zonation studies remain an opportunity for research.

Taxonomic consistency raises a great impediment to testing broad patterns in the deep ocean. Because the deep sea is so species rich and many species are rare, problems arise merging data from multiple studies and laboratories into a single analysis. COMARGE has melded comparable data for squat lobsters and nematodes, and others are
underway. Comparable datasets, sometimes requiring genetic barcoding, have revealed that many deep-sea polychaete worms, bivalves, and foraminiferans once thought to be cosmopolitan are actually mixtures of look-alike species that differ among regions. Comparisons have found look-alike, but distinct abyssal nematodes and isopod crustaceans. With common databases and taxonomic workshops, CeDAMar can now compare broadly. They proposed that on abyssal plains under the Southern Ocean, larger isopods and polychaetes may be confined to productive areas, but smaller protists may be broadly distributed.

This story of latitude, depth, and accompanying zones cries for resolution of its uncertainty, and points to the isolated vents, seeps, and plains that offer contrasts like those between gardens and deserts, and perhaps insight from local scales to the broader ocean.

When are “deserts” not deserts?

Planet Ocean offers many specialized environments for species (Figure 8.3), some that are toxic for many, but offer opportunities for others. On continental slopes, the environment changes over distances of centimeters to thousands of kilometers and timescales of millions of years to seasons. These changes offer diverse niches for many species, including some without relatives on land. Abundances and diversity of organisms
are less in the deep open water down to the seafloor because food particles
sink quickly through and accumulate to fuel the seafloor community.

Unfortunately OBIS has fewer data in this mid range than any other ocean
environment (Figure 8.4). Despite forbidding depth, darkness, pressure,
heat, and chemistry, specialized forms have evolved in hydrothermal
vents and seeps.

Vent specialists recognize six biological provinces defined by
tectonic plate slips below another (Figure 8.5), hydrothermal vents
open up. There, seawater percolates through cracks into the upper mantle,
is superheated at high pressure, and enriched in hydrogen sulfide,
methane, and minerals. These provinces have evolved their own suite of
species, some endemic and some cryptic. Vents remain to be discovered
in unexplored regions of the deep where the seafloor is spreading and
slipping.

ChEss discovered vents in the Lau Basin in the southwest Pacific, in the
East Pacific Rise in the southeast Pacific, and on the southwest Indian
Ridge of the southern Indian Ocean. These new locations built on known biological provinces, but new vent fields in the South Atlantic portion of the Mid-Atlantic Ridge may change current provinces. ChEss also discovered the hottest (407 °C) and deepest (4,100 meters) vents known so far.

Where the seafloor spreads ultra-slowly near the Azores, temperature and venting is low and the faunas of newly discovered vents resemble slope and seamount communities rather than other vents. ChEss discovered more than 10 new seep sites north of New Zealand, including one 180,000 square-meter area that is one of the largest globally. Vent and seep communities overlapping other areas of the western Pacific may represent a new province of seep and vent faunas. In the Nile Deep Sea Fan ChEss also found new hydrocarbon seeps at 1,000–3,500 meters depth, and hydrothermal activity in the Norwegian Sea and Arctic Ocean.

Across the deep-sea floor and through evolutionary time, faunas have colonized and diversified. Shallow-water isopods colonized the deep ocean during four periods, diversifying in abyssal habitats. Evolutionary history links shelf, slope, and abyssal environments. In the Southern Ocean, species of isopods and polychaetes invaded slopes from shelf or abyssal origins, whereas shelf and slope mollusks differ. These species pools comprise a diverse Southern Ocean fauna that surprised taxonomic
experts. In contrast, isolation of the Mediterranean Sea from the Atlantic by the shallow sill at the Strait of Gibraltar, in concert with major disturbance, has created an impoverished deep-sea biota that lacks major groups of echinoderms and glass sponges. Still, Mediterranean nematodes are relatively rich and areas that trap food material create hot spots of activity.

Generally, abyssal species appear widely distributed among basins, some more so than on slope depths. Most, but not all polychaete worms occur widely. Some cosmopolitan polychaetes, crustaceans and foraminiferans span basins, while others are limited to specific regions. Many abyssal species colonized from the continental slope and their widespread distributions reflect slow adaptation and evolution in the abyss. Nevertheless, areas of the abyssal Pacific have evolved characteristic fauna and many foraminifera and nematodes are truly abyssal in origin, distinct from slopes and distinct from other regions.

At hundreds to thousands of kilometers, ocean currents move water masses on and off continental slopes, changing oxygen concentrations, temperatures, and currents. These, in turn, alter patterns of large seafloor invertebrates and fishes. Currents create patterns of sediment and species across hundreds of kilometers. Sediments that cover slope environments are less uniform than they look. Steady winds push surface waters.
offshore and nutrient-rich waters rise to the surface. Biological production
increases and more detritus sinks to the seafloor. Beneath the Canary,
California, and Humboldt Currents, abundant detritus decays, depleting
oxygen and generating hydrogen sulfide that supports mats of specialized
bacteria that dominate oxygen-minimum zones.

Some canyons and ridges span hundreds of kilometers, while mid-
ocean ridges extend thousands of kilometers. Canyons channel food from
continental shelves down slope, supporting abundant fish, sponges, and
other invertebrates. Sediment composition and elevated food material
often contrast with the surrounding slope, elevating biomass and
abundance, but depressing diversity. Canyons link slopes and the abyss to
adjacent shelf habitats. On the continental slope of the Gulf of Guinea off
Africa, the Congo River Canyon and Channel transport food for
megafauna and others into deeper water on the abyssal plain.

Seamounts also contrast with surrounding abyssal plains and
continental slopes. Seamounts differ in depth below the surface and height
above the seabed, isolation, and age. Flat-topped seamounts, *guyots*,
accumulate sediments, but steep sides expose bedrock and coarser
sediments. Currents, oxygen and chemistry, light, temperature,
substratum, and productivity also influence seamount biota. Only about
250 have been sampled enough to say much about their species or to draw broad conclusions on diversity and endemism.

Productive seamounts have been fished since the fourteenth century, and attracted industrial trawling in the 1970s. Their unique isolation, geology, and productivity have intrigued biologists since the late 1950s and have recently generated a pulse of interest catalyzed by CenSeam. The CenSeam SeaMountsOnline database coordinated research, enabled broad-scale analyses, and revealed key knowledge gaps.

How do seamounts contribute to local and regional species pools? Though historically considered diversity hot spots, that view is changing. Some species on the most isolated seamounts are endemic, but recent exploration finds the same species live on seamounts and adjacent deep-sea areas, and there is no evidence of elevated seamount diversity. Many seamount corals and fishes occur widely and sometimes globally, genetically similar to populations on margins or near oceanic islands. But differing proportions of species may be one way that seamounts contribute to the riot of species in the deep ocean.

Seamounts may contribute more to deep-sea abundance than to diversity. Upwelling around seamounts recirculates water, amplifies waves, and creates internal waves that enhance productivity and retain offspring. Phytoplankton near seamounts are abundant, but insufficient for
the many fishes and other organisms that must also depend on food carried in currents that accelerate around seamounts, or on suitable prey items in the migrating zooplankton. Scientists have found only mixed evidence that the complex three-dimensional seamount corals increase diversity of other species, although cruises along the Mid-Atlantic Ridge found 40 species of deep-water corals with elevated fish diversity.

The Mid-Atlantic Ridge (MAR) bisects the Atlantic Ocean as it extends above the abyssal plain (Figure 8.5). Spanning water masses and latitude, it offers unique opportunities for discovery on diversity, distribution, and abundance. MAR-ECO found abundant copepods in the upper 100 meters, euphausiids peaked in the upper 200 meters, and decapods peaked at 200–700 meters. Gelatinous species peaked from 400–900 meters. In contrast to sharp declines below 1,000 meters in most ecosystems, open-sea pelagic fish biomass peaked at 1,500–2,300 meters, perhaps because the benthos of the ridge provided a food source for the pelagic fishes.

Abundant demersal, or bottom, fishes at the summit of the ridge declined with depth. For open-sea and bottom fishes, depth was more important than latitude. Surprisingly, sharks, skates, and rays are rarely, perhaps never, found below 3,000 meters, where their energy demands and the limited food in the abyss may exclude them.
Along the Mid-Atlantic Ridge, water masses define zooplankton pattern. The *Sub-Polar Front* between water masses creates a barrier for zooplankton, seabirds, and whales. Because bottom topography shapes water masses, it influences dolphins, sei whales, and sperm whales that congregate in surface waters thousands of meters above. Closer to the seafloor, large, adult fishes dominate, many in spawning or near-spawning condition. Ridge systems may be spawning and biomass hot spots, a hypothesis strengthened by the discovery of small, rare juvenile orange roughy and postlarval blue hake.

Manganese nodules on the abyssal plains create benthic habitat on scales of centimeters to kilometers, with higher species diversity than other areas nearby. During a 20 year study of the Porcupine Abyssal Plain southwest of Ireland, CeDAMar researchers discovered major increases in the lowly sea cucumber *Amperina rosea*, a major player in deep-ocean carbon cycling. Some species did not change, but protists and meiofauna were affected by increased food and *Amperina* burrowing. While small bacteria and meiofauna dominate numbers on abyssal plains, larger species dominate energy transfer. These changes were linked to increased food from surface waters as conditions changed. Though the 20 year study focused on changes over time, it also illustrates how food descending from above affects species composition far below.
Where abundant food accumulates and decomposes, methane and gas hydrates bubble up and support specialized bacteria on wood, whale carcasses, and OMZs. Communities on whale carcasses and wood falls, pockmarks in sediments, mud volcanoes, large microbial mats, and methane and hydrocarbon seeps all depend on these specialized bacteria and archaea. These habitats only span the area of a few football fields or less. Animals have ranges of tolerance to low oxygen and methane concentrations that define where they live. At smaller scales still, animals clustered at seeps modify chemistry to create unique habitats, providing habitat, refuges, and food. On smaller scales of centimeters to millimeters, small invertebrates create habitats for microbes, adding to the species pool. In addition to habitat, biological succession and inhibition contribute to species patterns and abundances.

Despite their heat and toxic emissions, hydrothermal vents support much life. The water cools from 350 °C to the ambient 2–3 °C in just a few meters. Until diluted, the abundant hydrogen sulfide, dissolved metals, and absence of oxygen start a gradient lethal to most life. These gradients create a range of microenvironments for free-living microbes and microbes living inside larger hydrothermal-vent organisms. Clams and tubeworms at vents have genes, enzymes, and other adaptations to tolerate these conditions and feed from the intense microbial production. Metals in vent fluids accumulate in animals and pass from prey to
predators. As in seeps, vent animals create microhabitats for other species between their tubes and shells, adding to the diversity of vent species that range from abundant to rare. Vent isolation encourages endemism, leaving 70% of known vent species unique to a region. Vent larvae are sometimes retained within the vents they came from.

These small-scale environments are transient in the staid deep sea. As minerals flow from vents they precipitate to form solid chimneys that grow to 40 meters and eventually topple from instability. Vents ebb and flow as new cracks form in the crust and others close. The landscape of the habitats may persist for decades, years, or less, supporting a few specialized species, but then disappear. The desert oases come and go.

**Stepping stones to a diverse deep sea**

Many species occur only in the isolated vents or seeps. Some live at hydrothermal vents, but not elsewhere, whereas others also live on whale carcasses. Because most of these species move only as larvae, how do they find these “islands” of heat and toxins, and evolve endemic only to that location? However the inhabitants find them, the isolated vents and seeps add deep-sea diversity. Whale carcasses support a rich fauna locally, including a newly discovered species of lancelet and rare species of a bottom-living comb jelly and snail. A single whale carcass has as many
species as global seeps combined or all species from a geographic cluster of vents. Unique species in these specialized environments are modest in number, but add significantly to regional diversity.

Habitats of many types and sizes (Figure 8.3) transform the “desert” landscape under the ocean into complex environments defined by temperature, seafloor composition, necessary food, and oxygen and chemical gradients. Biology also creates habitat. Microbes feed their living hosts in a mutualism, where one organism depends on another. Some species wait until others first make the habitat suitable, so crabs may not appear at vents until tubeworms colonize first.

The deep human footprint

It hardly seems possible that human activities on land leak out to the remote and immense deep ocean, but they do. They act in concert with activities at sea to create an array of current and future threats. Recent evidence links biodiversity to deep ocean health, where seafloor biodiversity enhances productivity and cycling of material. This COMARGE discovery suggests how the loss of species could compromise health in the deep sea.

Pollutants from land make their way via drainage into the nearshore environment and then into the deep ocean. They flow through canyons
that carry lead and other metal contaminants. Elevated concentrations of toxic DDT and PCBs show up in deep-sea fauna.

Only decades after depletions of coastal fisheries drove fishermen deeper and deeper, some deep-sea species are now depleted and endangered. Lucrative deep-sea fisheries collapsed and simultaneously drove non-target species to near extinction as fishing gear destroyed deep-water corals. Bottom trawling down to 1,600 meters may decrease abundance to 2,500 meters as fish move into vacated habitat. The footprint of deep-sea fishing is broader than the targeted areas or species as trawls bring up tonnes of damaged biota that is unceremoniously dumped over the side.

In addition to uprooting fragile sessile fauna on seamounts, fishing removes fauna that are slow to reproduce, produce a few offspring, grow slowly, and live long. Bottom trawls quickly eliminate deep-water coral habitat and other invertebrates. Fishermen quickly find fish populations concentrated around seamounts and exploit them, bringing rapid collapse. Most deep-sea fisheries are biologically unsustainable, perhaps a moot point because management and enforcement are difficult in international waters where many seamounts occur. Fishing has affected even remote and patchy seep environments on the California margin, the Chilean margin, and newly discovered seeps near New Zealand, where fishing
gear arrived before scientists. Recovery from fishing takes decades or
longer for seamount corals and fishes.

Cost has prohibited mining the deep-sea bed, but rising metal prices
may make deep-sea mining profitable by the year 2025. Millions of square
kilometers of the abyssal seafloor covered with golf-ball to softball-sized
manganese nodules rich in iron, manganese, copper, nickel, and cobalt sit
deep below low productivity waters of the Pacific and Indian Oceans.

Foreseeing nodule mining, nations have staked seabed claims. To test the
vulnerability of the Pacific abyss, CeDAMar investigated whether most
manganese nodule species are endemic and vulnerable or cosmopolitan
with refuges elsewhere. Some suggest abyssal species reproduce on the
continental slope and marginally survive in the abyss. CeDAMar,
however, found a characteristic fauna in the Pacific abyss, with many
foraminiferans and nematodes unique to the abyss. Molecular analysis
uncovered many cryptic polychaete species endemic to the Pacific abyss.

Mining would disturb seafloor, seamount, and hydrothermal vent
environments. Companies now plan to mine the gold, silver, copper, and
zinc in chimney-like deposits at vents. They have already begun
environmental-impact studies with plans to exploit these deposits within
the next decade, though knowing little of the consequences for vents.

Seamounts are also hot spots for cobalt-rich manganese crusts, manganese
nodules, and polymetallic sulfides that may be exploited for precious and
base metals.

Oil drilling pumps hydrocarbons from thousands of meters below the
ocean’s surface. Drill-cutting spoils smother organisms and add enduring
toxic chemicals with poorly known effects out to tens of kilometers. Other
commercial activities threaten, from mining methane hydrates to storing
CO₂ in seabeds or fixing it at the surface by iron fertilization. Knowledge
of CO₂ disposal effects on benthic organisms is equivocal. Finally,
scientists themselves must not damage or spoil fragile hydrothermal vents
and seeps as they work to uncover their secrets.

Global warming could affect the deep ocean. Global warming might
stratify tropical and temperate oceans, reducing nutrients for
phytoplankton and reducing food export into the deep. Lower abyssal
abundance and changing species will follow, and because changes are
expected over massive areas, extinctions are likely. Less mixing of
oxygen into the deep would widen OMZs in the tropics. The northward
extension of Humboldt squid in warming waters of the Oregon,
Washington, and Alaska coasts may be harbingers of changes that
warming will cause.

The global ocean paid a price for taking up almost a third of the
additional CO₂ that humans added to the atmosphere during the twentieth
century. Dissolved CO₂ increased ocean acidity measurably and acidity
dissolves calcium carbonate, the stuff of coral skeletons, among others. In
the North Pacific, coral distributions are already changing. Echinoderms,
mollusks, foraminiferans, and corals are candidates to suffer this century
if acidification worsens, with cascading effects on other species. Low
oxygen waters in OMZs are already more acidic than elsewhere and as
they expand will amplify acidification effects.

The immensity, diversity, and unknown mysteries of the deep ocean
heighten fears we will harm it. Its immense diversity and hot spots of
endemism suggests a trove of “sunken treasure” that trumps any pirate’s
chest. One deep-sea trawl in the deep Mediterranean retrieved more trash
than animals (Figure 8.6). As a 20-year-old undergraduate, I dissected a
redfish hardly big enough for a single meal. As I worked, a thought gave
me pause: the redfish under my knife was much older than I was.

But the deep-sea story is mostly a very good story and an exciting one.
Scientists aboard the Challenger expedition could hardly have dreamed of
the array of tools available today (Figure 8.7) that opens up the expanse of
diversity and unknown mysteries of the pristine deep to scientific
exploration. By playing their peculiar role of discovering causes and
effects well, scientists can convert unknowns into knowns and lessen the feared harms to the future ocean.

Insert Figure 8.7 here
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Table 8.1 The top ten reasons why the deep sea is special.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>We cannot extrapolate knowledge from other environments to the deep sea because of its special characteristics and dominant organisms.</td>
</tr>
<tr>
<td>9</td>
<td>The interconnected deep ocean and its large size make taxonomic coordination difficult, but vital to understand broad-scale patterns.</td>
</tr>
<tr>
<td>8</td>
<td>As the most pristine marine environment left on Earth, it is one of few places where we can study natural processes where human impact is minimal.</td>
</tr>
<tr>
<td>7</td>
<td>Because they are so distant and often in international waters, the management and conservation of the deep sea is particularly complex and undeveloped.</td>
</tr>
<tr>
<td>6</td>
<td>The human footprint is creeping deeper into the ocean with unknown consequences because of many rare species, special habitats, and slow-growing species that produce few offspring.</td>
</tr>
<tr>
<td>5</td>
<td>Deep-sea habitats include some of the most unique and spectacular habitats on Earth, including some that changed our views of how ecosystems work.</td>
</tr>
<tr>
<td>4</td>
<td>The rate of discovery of abyssal nematode worms and abyssal plains species shows no sign of levelling off, illustrating the magnitude of the unknown.</td>
</tr>
<tr>
<td>3</td>
<td>The deep sea covers more of Earth than all other habitats combined, yet total sampling covers only a few football fields in area. Surely we must do better!</td>
</tr>
<tr>
<td>2</td>
<td>Just about every deep-sea sample has new species in it, and in some areas unknown species in a sample can greatly outnumber the known.</td>
</tr>
<tr>
<td>1</td>
<td>Entirely new types of deep-sea habitats have been found steadily over the last 100 years and new discoveries don’t seem to be slowing down.</td>
</tr>
</tbody>
</table>
Chapter 9

Changing ocean

Natural change in Planet Ocean

Tides change the ocean daily, and cause many of the patterns around the ocean rim. While we hardly notice a small change in tide along the Australian coast, tourists flock to see a 16 meter rise and fall in the Bay of Fundy, floating and then grounding fishing boats. El Niño affects the weather far and wide, but it throttles upwelling of cold, nutrient-rich water off Peru that feeds large fish populations, which in turn sustain abundant seabirds. The ocean changes for myriad reasons.

Preserved Danish fish bones show species composition changed during a warm period some 6,000 to 9,000 years ago. Baltic Sea herring, *Clupea harengus*, and other species declined in cold waters in the late 1600s, as did salmon, halibut, and cod in the Barents and White Seas. Preserved fish scales from sediments off the California coast show fluctuating anchovy and sardines over the past 1,700 years, long before humans arrived. Fisheries biologists reconstructed a Danish fjord fishery from 1667 to 1860 and concluded that overfishing collapsed herring, but a major storm
that opened the fjord to the North Sea and saltwater intrusion lowered eel
and whitefish numbers. Thus, some collapses were natural, and another
avoidable.

The ocean changes naturally, but now we humans too drive change.
What would the ocean look like if we had not? We don’t know because
early fishermen were the first to sample the ocean, and their sampling
expanded quickly and efficiently as small fishing boats propelled by
human muscle or wind were replaced by powerful trawlers that haul
heavy fishing gear across the seafloor and through the water. Scientists
seek compelling proof to understand change, but data that show the ocean
before exploitation simply don’t exist. The analogy of a “human
footprint” on the ocean is appropriate because footprints tell you someone
was there, but not what they changed.

Changing oceans and changing marine life extend well beyond our
attention spans or the decade of the Census. We suffer “shifting baseline
syndrome,” where our lifetime experience colors our expectation of a
“healthy” ocean to one that may differ from historical reality. I was
surprised when the (now deceased) Ransom Myers, a leader within the
Census and a master of global data integration, noted that walrus were
hunted to extinction in Newfoundland many years before I was born.
Although a native resident who studies Newfoundland waters, I did not
know walrus had ever lived there and had suffered my own shifting baseline syndrome.

We can see recent change, but must infer past changes from archaeological sources and other historical clues rather than surveys of the present ocean. Accordingly, the Census’ *History of Marine Animal Populations* (HMAP), established the new discipline of environmental history. Tim Smith, one of the founding leaders of the HMAP project, describes it as an attempt to correct “historical myopia.” Using numbers standardized for historical fishing effort, biodiversity metrics, and statistical models, HMAP asked how the diversity, distribution, and abundance of marine life in Planet Ocean changed over thousands of years. They worked closely with the *Future of Marine Animal Populations* (FMAP) project, which focused on recent changes in ocean life, and in some cases how those changes may foretell the future.

**Early remains of oceans past**

Archaeological evidence provides uneven “glimpses of the past.” Prehistoric man drew seals, auks, and jellyfish on cave walls in the Grotto Cosquer in France 18,000 years ago. Boats from Egypt in 4000 BC and China and Kuwait from 7,000 to 7,500 years ago tell us ocean transport began early, but we are less certain when boats expanded fishing effort. In
2400 BC, in the oldest known civilization, Sumer, hundreds of fishermen caught more fish in the Tigris-Euphrates with hook and line than they could consume. Prior to nets and fishing boats, ancient fishers relied on hooks and worked from shore, suggesting fish were a minor dietary source. But before accepting that view, remember that nets are poorly preserved, and some modern fishermen catch many fish while standing on shore.

When first did boats extend fishing nets, increase catches, and when did salting preserve the catch for storage and transport? Before salting, which dates back to the seventh century BC and possibly to 2400 BC, fishermen had no way to preserve their catch. Fishing very early in the morning before the midday heat bought a little time, but still limited what they could catch and deliver.

Images of tuna and sturgeon on early Greek coins (about 400 BC) suggest they were part of that culture. Imagery on shields from 400 BC excavated from the Northern Black Sea show that early nomads fished, a finding seconded by abundant fish bones in household middens. By the early first century BC, Romans operated fish-processing facilities in Spain, Portugal, and Morocco. Many facilities were built near coastal “pinch points” to funnel migrating or spawning tuna, mackerel, and eels into nets. We may never know when these activities had any appreciable
impact on fish populations, but they mark the beginnings of “commercial”
fishing, and wide distribution of fish products through Western Europe by
the first century AD, as Roman influence spread.

The best-documented changes are for fishes. Shells of clams and other
mollusks preserve well on land, however, and demonstrate early human
exploitation of islands and coasts. Large mollusks (megamollusks) have
been used as food and ornaments for over 450,000 years, and have
contributed to human demography and migration for 150,000 years.

Between 1200 and 1500 AD in the New World off Venezuela, humans
harvested more than five million conches, leaving a massive pre-
Columbian midden of queen conch (Figure 9.1). Still, humans did not
depend enough on mollusks to drive them to extinction.

Paintings tell a story of change in northern European waters; Frans
Snyders’ paintings of fish markets at the turn of the seventeenth century
show an abundance and variety of fish no longer seen 300 years later in
European waters. But images, bones, and shells give glimpses of what
humans fished rather than its impact, and written information is more
telling.
Early writings about oceans past

HMAP also used ships’ logs, surveyors’ and pirates’ diaries, tax records, and medieval cookbooks and restaurant menus to look back in time at how humans have changed the ocean. Early Greek writing confirms some archaeological conclusions. The Hippocratic Regimen II of about 400 BC refers repeatedly to salted fish. The Greek writer Oppian’s Halieutika was the first treatise on fishing, and describes fishermen using boats in the first century AD. Pliny the Elder’s written fish recipes tell us fish was a staple food more than two millennia ago at the time of the Roman Empire. Perhaps garum, the fermented fish sauce that was a Roman staple and transported throughout Western Europe, was the antiquarian version of McDonald’s “special sauce.”

As western civilization and human populations spread, fishermen and the food they landed grew in numbers. By 1000 AD in the North Sea, migrating salmon and eel, and later cod, ling, and herring caught by boats, were major staples. In the 1200s, the Baltic Sea herring fishery was a major industry. Giovanni Caboto, sent by England in 1497 to find New World fish to replace declining European stocks, described cod in Newfoundland waters so plentiful they could be captured in baskets.
Unnatural changes in Planet Ocean

1 Planet Ocean continued to feed more and more people, but fishing expansion and intensification was taking a toll on the natural environment.

2 Impacts appeared centuries ago, even before industrial fishing in recent decades. Sparse populations of indigenous people probably harvested, but had little impact on shellfish and fishes. But the evolution of commerce moved fishing sequentially from estuaries to shelf to open ocean.

3 Depletion of estuaries and densely populated nearshore regions dates back hundreds to thousands of years, shelf fisheries began precipitous declines within the last 50 years, and deep-sea and oceanic species declined mostly in the last few decades.

4 Some took note long ago. In 1376, British fishers petitioned the British Parliament that trawling was destroying “the living slym and underwater plants,” and that catches of smaller fish were declining. But fishing continued to expand. By the fourteenth century, sturgeon from rivers flowing to the Wadden Sea had disappeared from markets, becoming a food only for the aristocracy. By the sixteenth century, annual Danish fish catches were at 35,000 tonnes, and Dutch fishermen landed 75,000 tonnes annually before major declines in the 1700s. Poor fishing practices collapsed the Danish herring fishery by 1830, and it has never fully recovered. As markets in Europe became more global around that time,
seabirds, marine mammals, and reptiles declined in many areas. When
motorized vessels were launched around 1900, declines in commercial
salmon and cod in Denmark quickly followed. The increased cost of
running a fishing boat simultaneously created a need to catch more fish.

Marine fisheries shaped patterns of trade and human settlement of
North America from the 1500s onward. Early wars over fishing rights, the
trade routes that ensued, and patterns of human settlement closely linked
to the development of seventeenth and eighteenth century cod fisheries in
the western Atlantic. Increased exploitation led to serious decline that set
the stage for stock collapses in recent decades; many have still not
recovered. The past view of resilient fish stocks easily recovered with
short-term closures is quickly fading.

**Recent change in Planet Ocean**

Where HMAP ends, FMAP picks up and carries the story of ocean change
through the present. Australia is unique because baseline data pre-date
exploitation, but the story they tell is familiar. Australian fisheries only
began to ramp up at the start of the twentieth century, but motorized boats
and gear were already available, and by the 1930s declining catch pushed
fishermen into deeper and deeper waters in pursuit of fish. Eventually,
specially designed fishing gear and electronic devices to locate fishes on
the seafloor would soon exploit areas whose rugged bottoms had previously protected them from fishing. Orange roughy were quickly and efficiently fished to commercial extinction on distant seamounts with much collateral damage to other species. Although elaborate fishing gear accelerates rapid decline, it is not a prerequisite; Jamaicans fished coral reef fishes beyond sustainable levels a century ago with simple fishing gear such as hook and line.

Recognizing declines in fish stocks, fisheries science grew quickly after World War II with widely adopted fisheries models of Ricker, Beverton and Holt, and others. Although these tools helped in some cases, they demand good data that extend back over time. But time series data are difficult to interpret because fishing effort changes in space and time, as do discards, and erroneous catch reporting. Even different vessels using similar bottom trawls catch at different rates. In some cases fisheries management has produced recoveries, but many fisheries remain depleted long after we try to manage them.

Good knowledge helps. New analytical approaches can determine when depensation occurs, where a population drops so low that recovery is near impossible. In an example of the power of knowledge, new analysis of coho salmon and alewife populations ruled out depensation so fisheries
managers could opt for less extreme measures than completely shutting down a fishery.

Nevertheless, depletions continue, one species after another. Serial depletion fishes down one species, and then moves on to deplete another, eventually “fishing down the food web.” In Newfoundland, cod followed haddock and now crab and shrimp follow cod. Fishermen move through multiple species of decreasing economic value, and begin to target “underutilized species” that are little studied and therefore even more difficult to manage.

Factory freezer trawlers scoop up tonnes of fish in a single trawl, accelerating declines. Industrialized fisheries today can reduce community biomass by 80% in 15 years. We are far more efficient ocean predators than we were 100 years ago, but also far more wasteful as we throw tonnes of discard over the side. Evolving technologies and faster boats depleted whale species in series, beginning with slow, inshore species like right whales before moving to faster offshore species like sperm whales. Again we fish the most valuable or accessible before moving on to less valuable or hard-to-catch species.

Declining fisheries bring social and economic change, mostly for the worse. The fishing industry directly employs some 200 million people and provides some 5% of the total protein and 20% of animal protein in
human diets globally, and much more in poorer coastal nations. Tuna remains valuable; a single Pacific tuna, *Thunnus orientalis*, fetched $174,000 US in 2001! Because the stakes around the world are so high, reports on overfishing attract attention and controversy. We now reluctantly see global-scale fisheries collapses. “Perverse incentives” to upgrade boats or supplement seasonal employment save jobs, but escalate exploitation, and although some argue that removing these subsidies would eliminate marginal fisheries and allow stocks to rebuild, this is a cruel solution for fishermen with mortgages and hungry families.

**What have we lost?**

In 1883, naturalist Thomas Henry Huxley optimistically stated that “I believe, then, that the cod fishery, the herring fishery, the pilchard fishery, the mackerel fishery, and probably all the great sea fisheries, are inexhaustible; that is to say, that nothing we do seriously affects the number of the fish. And any attempt to regulate these fisheries seems consequently, from the nature of the case, to be useless.” His contemporary, Edwin Lankester had a different view. “If man removes a large proportion of these fish from the areas which they inhabit, the natural balance is upset.” The voice of the industrial boom was loud, as it often is today and many changes would follow. Consider what we lost that damped the optimism of Huxley’s view and tipped history toward
Lankester’s fear of humanity’s power to unbalance a system as vast as Planet Ocean.

Great auks and Atlantic gray whales were extinct in the North Sea by the late medieval period and disappeared globally not long after. New England and Newfoundland (Figure 9.2) fishermen once caught 1 to 2 meter cod that were sometimes bigger than them, and Chesapeake oyster beds produced 30 centimeter oysters that had to be cut in pieces to be eaten. In the Wadden Sea, some 20% of the macrobiota, those organisms visible to the naked eye, disappeared or seriously declined over the last 1,000 years. Abundant large fishes, sea turtles, and marine mammals that once populated coral reefs are ignored in modern textbooks because they were gone before researchers arrived in the 1950s. Ships’ logs show that cod biomass estimates for Canada’s Scotian shelf declined some 96% from 1,260,000 metric tons in 1852 to 50,000 metric tons in 2005.

Archaeological data from eastern Canada show two centuries of decline, mostly from overfishing. European arrival in the 1700s caused declines by the 1800s in diadromous fishes, which use both fresh and salt water, followed by declines in groundfish and the extinction of six bird and three marine mammal species from the region by 1900. These declines set the stage for collapse of groundfish by the 1970s that would
be mirrored in other areas of Atlantic Canada in the decades that followed
and the grim state of many fisheries today. Since exploitation began, the
weight or biomass of 256 species of large marine mammals, birds,
reptiles, and fishes, declined 89%, and individual species declined by 11–
100% (Figure 9.3). The total weight of large predatory fish has fallen to
10% of pre-industrial fishing levels. These changes mirror declines in
biodiversity, the array of species present. Our knowledge of highly valued
commercial species is far greater than our knowledge of others, so many
biodiversity changes go unobserved.

HMAP reconstructed abundance and distribution of whales from logs
of whaling ships to produce maps that tell of 70,000 whale encounters and
locations during the nineteenth century. These data show frequent and
alarming extirpations, or local eliminations of marine mammals. The
oceans between east Australia and New Zealand teemed with 27,000
southern right whales, roughly 30 times as many as today. Using genetic
diversity and mutation rate to estimate past population sizes in whales,
researchers found that Pacific gray whales, *Eschrichtius robustus*, were
three to five times more abundant before whaling than they are now. And
these whales affected sediment resuspension and food webs far more than
today’s smaller populations.
Trade records show Caribbean marine turtles have declined precipitously. Nesting sites have disappeared and green turtles, which numbered a staggering 15 to 116 million when Columbus arrived, number only 100 nesting females today.

Dusty sales records, fishery yearbooks, and other written material showed HMAP that bluefin tuna arrived in northern European waters by the thousands each summer until an industrialized fishery geared up in the 1920s and literally filled the floors of European fish markets (Figure 9.4). Before World War I, bluefin were rarely caught, but with advanced technology, fisherman in the 1920s were catching 50 to 100 kilogram tuna, and some as big as 700 kilograms. One sports fisherman landed 62 bluefin near the island of Anholt near Denmark in 1928. Abundant tuna in Denmark and Swedish waters inspired the formation of the Scandinavian Fishing Club that held bluefin tournaments until the early 1960s. By 1949, fishing was removing 5,500 tonnes, but by the 1960s catches had plummeted, and bluefin in the North Sea was commercially extinct.

Photos of the winner of Florida fishing contests (Figure 9.5) showed that in 1950, large groupers and sharks almost 2 meters in length and weighing 20 kilograms were the prize winners. By the 1970s fish size had
decreased noticeably, and in 2007 the contest winners were small
snappers averaging 34 centimeters in length and 2 kilograms in weight.

Hammerhead, thresher, and white sharks have declined in the
Northwest Atlantic more than 75% in the last 15 years, and other sharks
by more than 50%. Oceanic whitetip and silky sharks, which were the
most common sharks in the Gulf of Mexico until the 1950s, have declined
more than 99 and 90%, respectively. In the Mediterranean Sea, sharks
have declined 99.99% from historical abundances in the early nineteenth
to mid-twentieth centuries. These declining numbers illustrate a shifting
baseline that leave few people realizing these sharks were once prevalent.

Like sharks, skates, and rays, many deep-sea species that grow slowly,
reproduce late in life, and produce relatively few offspring, cannot be
fished sustainably.

Forecasting change is uncertain and controversial. A projected 100%
collapse of global fish stocks by 2048 drew harsh criticism. Reanalysis did
find that although about 63% of global fish stocks required rebuilding,
some levels of exploitation have moderated to sustainable levels and
populations will survive as long as critical thresholds are not exceeded.

Still, these analyses were based on the best-known fisheries in the world,
with the best experts possible, and excluded lesser-known areas like the
tropical Pacific that some believe are fished excessively and unsustainably.

**The cascading effects of fishing**

Fishing effects reach far and wide, well beyond a single species. Industrial fishing alters food webs by removing top *apex* predators. When trawl gear scrapes the seafloor, much like logging clear cuts a forest, it destroys cold-water corals and other living and non-living bottom habitat. Different fishing gears vary in how selectively they catch fish; some gears remove just about everything they encounter, whereas others target more precisely. Catching unintended species, known as *bycatch*, when fishing for other species changes the ocean. Sea turtles, whales, sharks, and seafloor invertebrates become bycatch in shallow- and deep-water fisheries. Modifying fishing gear increases selectivity and decreases bycatch but imperfectly, so the problem is ongoing.

The effects of whole-scale removal of apex predators can cascade through the entire food web, altering species that are not directly related to fishing. Precipitous declines in all 11 species of great sharks in the northwest Atlantic ecosystem allowed increases of cownose rays that prey on scallops and may have caused the demise of a century-old scallop fishery. In the Pacific, declines of 21% in numbers and 50% in size of
sharks and tuna since the 1970s coincided with increases of a few small
species that were insufficient to replace the lost biomass. In the Gulf of
Mexico, removal of large sharks meant other sharks had no predators and
subsequently increased. Between the 1970s and the 1990s in the
Mediterranean Sea near Spain and Greece some of the highest steps from
the base to the top of the food web disappeared. Increased vulnerability to
extinction followed, and biomass at lower trophic levels grew. Fishing,
exacerbated by bycatch and habitat degradation, has reduced species
richness of coral-reef fishes. Increased runoff from land reduces water
clarity, increasing algal growth and decreasing coral cover, and all reduce
fish habitat and add to fishing impacts. These patterns can be generalized
as degraded ecosystems.

Sometimes collapse of one species lets another flourish. After Atlantic
cod, *Gadus morhua*, in Newfoundland collapsed, the abundance of one of
its prey, northern shrimp, *Pandalus borealis*, exploded. Some fishing jobs
were saved as a new industry chased northern shrimp. But fisheries
collapses usually force fishermen to chase ever smaller fishes of ever
lower economic value that must be harvested in higher numbers to yield
profit.
Ocean change beyond fishing

Before sewage treatment, one can imagine foul-smelling streets and canals in Shakespeare’s London or Rembrandt’s Amsterdam, and pockets of degraded coastline near large cities that date back many centuries. But the scale of coastal hypoxia from fertilizer runoff and sewage input has only been recognized in recent decades. Increases in atmospheric carbon following the second wave of the industrial revolution in the late 1800s and then in the 1950s are linked to slow and steady ocean warming since the 1950s. Only in the last decade have researchers linked this input to ocean acidification. They have even hypothesized that deep-sea environmental change is linked to warming surface waters and ocean acidity.

Hungry nations now look to mariculture – growing cod, salmon, and others – to replace collapsed wild stocks, but at a cost. Mangroves are destroyed to make way for shrimp and other mariculture. Mariculture finds the high protein diet needed by carnivorous fish by harvesting large abundances of low value ocean life – a strategy likened to trapping shrews and foxes to feed farmed wolves. Other species like mussels don’t require food supplement beyond natural sources, but habitat degradation and shoreline change still take a toll.
New analysis shows combined threats are collectively more damaging than the total of their individual effects, and multiple threats simultaneously affect some 41% of the global ocean. Experiments that simulated exploitation and habitat fragmentation demonstrated that populations decline 50 times faster when threats act together than separately. Although the overwhelming drivers of change are exploitation of animals and habitat destruction, adding invasive species and altered climate to the mix may speed change in coming decades.

For millennia the ocean has provided seafood, oils, furs and feathers, and medicines. It regulates climate, gas exchange and oxygen production, and nutrient cycling, and transports people and goods around the world. We relax on beaches and boats, which inspired our artists from Coleridge to Conrad to Hokusai to Doubilet to create beauty.

While the ocean worries us today, we can find hope in its beauty, which persists despite scars. Many fisheries flourish and continue providing protein to many. Mariculture helps, sometimes with little effect on the ocean when herbivores are cultured. We understand our footprint more clearly than in the past, and many work to sustain ocean biodiversity and abundance into the future. People care about the ocean
– even those who live far from its shores. Beyond 2010, humanity can learn more and manage better the changing oceans.
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Part III

From unknown to unknowable
Chapter 10

Planet Ocean beyond 2010

Accomplishments, many by the Census, during the last decade, foreshadow how the goalposts of the known, unknown, and unknowable will shift beyond 2010. Knowledge was extended back in time, providing new baselines of the ocean past that once seemed unknowable. Tools that made the ocean more transparent added knowledge of animal behavior, and new images of the diversity of ocean life. Electronic tags hitchhiked on animals around the ocean deep and shallow, far and wide, transmitting views of Planet Ocean as animal life sees them. Newly discovered species, habitats, and patterns changed our knowledge of the present Planet Ocean. Models project glimpses of future oceans.

Beyond 2010, scientists will explore changed oceans. Census leaders imagined the ocean in 2020 and beyond, and summarized their expectations in Table 10.1. The news is a mixture of the bad, easily predicted from past changes, with some good, arising from better information, communication, and their application to ocean problems.

Scientists will acquire more information, the subject in the final two boxes.
Recent additions to known diversity

Some 500+ research expeditions and countless nearshore samplings discovered thousands of new species from everywhere explored, spanning all the ocean realms. Exploration extended from the Arctic to the Antarctic, along shorelines onto coral reefs and into the Gulf of Maine. Exploration extended down the continental slope through seeps and vents into the abyss, and up onto seamounts and along the Mid-Atlantic Ridge. Exploration added knowledge of diversity of new species, their distribution around Planet Ocean, and their abundances. New knowledge was added for the smallest microbes and zooplankton and the largest whales. Some species thought to be extinct are now known to live.

New applications of genetic technology move cryptic and unknown species into the known and knowable, whether to compare microbes in a single sample, to contrast copepod crustaceans from distant locations in the global ocean, or to categorize untold numbers of previously unseen species from coral reefs. Discoveries of the hottest, deepest, northernmost, and southernmost vents, and the largest known cold seep on Earth all add
to the riot of species. Rarity is now thought common, and common is rare, with species from microbes to fish seen only once in all of human exploration, pointing to a plethora of life.

Recent additions to known distributions and abundances

While new species were being discovered, scientists have also been adding new knowledge about the distributions and abundances of known species. The OBIS central database reconciled vast and varied data on known ocean life into standardized and comparable form in collaboration with the World Register of Marine Species. OBIS works with WoRMS to put definitive names on all the 230,000 to 250,000 known species of marine life. Anyone in the world can access whatever their need over 22 million records (and counting) of individual ocean specimens now amassed in a single database (www.iobis.org). Global datasets and novel analyses populate new maps of ocean life that identify hot spots of diversity and abundance (Figure 10.1), some unexpected. Standardized sampling tools and strategies, with taxonomic catalogs facilitate the mapping and enhance less ambiguous and controversial analyses.

Thousands of tagged animals spanning 40 different species show new migration “highways” and “truckstops” far from land within fluid borders.
that animals “see.” Electronic sensors show the tagged animals’ view of Planet ocean as they move to feed and reproduce. They tell us that events on one side of the Pacific affect the other, and that events in the Antarctic link to those in the Arctic and the ocean between. Above the Mid-Atlantic Ridge the tagged animals move up and down as day changes to night.

New acoustic imaging of swaths of ocean shows well-organized schools of millions of fish that cover an area the size of Manhattan Island, assembling within minutes.

**Applications of the Census discoveries**

The Census shows a new way of conducting science with a global network of 2,600 scientists tackling complex questions with a suite of tools from traditional to cutting edge, from simple to complex. The power of one is the combined strength of many, creating new views and new excitement. Ocean biodiversity has moved from understudy to mainstage player, and the Census has led.

Ocean life is freshly visualized with new tools like Google Earth’s Ocean layer and other three-dimensional views that show the pattern and movement of ocean life. The appeal of marine biota is evident in the popular press and the findings of the Census, whether bad news on the
state of some organisms and ecosystems today, or the breathtaking and
inspiring imagery of new species that fascinates the public.

The Census moves fascination with “stamp collecting” on to
conservation of diversity, distribution, and abundance. Monitoring Arctic, Antarctic, and coral reef ecosystems closes gaps in knowledge. ArcOD participants work within the international Arctic Council to monitor how Arctic marine ecosystems respond to climate change. CAML contributed to the Commission for the Conservation of Antarctic Marine Living Resources’ decision to declare two Vulnerable Marine Ecosystems and protect them from long-line fishing. A new Census study shows most Marine Protected Areas (MPAs) today don’t conserve the reefs they were intended to protect, and they can’t offset declines in coral reef ecosystems. Managers have embraced CReefs tools in new plans to monitor acidification and coral reef health beyond 2010.

TOPP tagging data on black-footed albatross were used by the US Fish and Wildlife Service during international deliberations on conservation. The establishment of an MPA to protect loggerhead turtles off the coast of Baja California was spurred by TOPP findings, and the discovery of leatherback turtle migration highways has contributed by a resolution by the International Union for Conservation of Nature (IUCN) to protect leatherbacks in the open ocean. Knowledge of specific migration routes
shows where species are vulnerable and improves conservation of vulnerable species by reducing bycatch and trash. POST data on salmon survival in river dam systems shows that dam removal may not produce expected benefits.

CenSeam contributed to the United Nation’s *Food and Agricultural Organization* (FAO) to develop guidelines for sustainable management of seamount ecosystems and their fisheries. Classification and predictive tools on seamount distributions will aid in future development of seamount MPA strategies. ChEss scientists contributed to plans to protect a network of chemosynthetic environments and scientific guidelines and criteria to be considered by the *Convention on Biological Diversity*. A code of conduct for scientific study of hydrothermal vents has been developed with ChEss input, and is utilized by the *OSPAR Commission*, the lead agency on northeast Atlantic conservation. CeDAMar has worked with the *International Seabed Authority* to identify the need and strategy to create MPAs within manganese nodule areas of the abyssal plains.

The still unknown

During its decade the Census has clarified where gaps in knowledge remain to be filled beyond 2010. Different locations, habitats, seasons and
taxonomic groups provide needs and opportunities for research, some
more than others.

Discoveries of unknown species in the deep Southern Ocean seafloor
reveal one clearly neglected region ripe for exploration. The ignorance of
life beneath ice-covered regions of the Arctic and Antarctic holds
opportunity for new discoveries. Sampling polar ecosystems beneath the
ice during winter will produce surprising new discoveries. Many areas of
the deep sea, especially the meso- and bathypelagic zones encompassing
200–4,000 meters depth (Figure 7.1), and deep ocean trenches will likely
yield discoveries. Only a small fraction of global seamounts have been
sampled quantitatively. The discovery of vents and seeps in the Arctic and
Southern Ocean suggests more will follow, along with discovery of new
species. With more unknowns per square meter than anywhere in the
ocean or possibly on Earth, coral reefs provide opportunities for research
and threats give them priority.

A taxonomic inventory of marine life requires a census of microbes,
which are far more unknown than known. Small invertebrates, particularly
in the deep sea, are little known. Although new species of fish will be
encountered, particularly in the deep sea, they will be discovered at a
lower rate than will invertebrates.
Biodiversity and management needs

Some ocean biodiversity research needs span from applied to pure research. Little is known about how the riot of species is linked to the ways the ocean functions, and whether species loss will compromise ocean health. This gap links to a need to understand the resilience of the few relatively pristine ecosystems that remain on Planet Ocean – the deep sea, Arctic, and Antarctic. These systems will face increasing pressures from human activities, as will other ocean ecosystems. We know more about where adults and juveniles move in the ocean, but little about how their eggs and larval offspring are transported and how their fate affects abundance and spatial pattern in nature. Both of these questions have relevance to MPA design and management of species from fishes to scallops to lobsters. We also need to know which habitats are critical to different species, and where those critical habitats are found.

Abundance, the third of the Census triad has proved more elusive than diversity and distribution. Knowing whether marine life, its numbers and biomass, is growing or declining rests on reliable measurements of abundance, a clear priority beyond 2010. Surveyors finally have a comprehensive framework into which they can put information of more than 200,000 species.
The unknown, but soon knowable

We will soon become “virtual fish” that experience the entirety of the fish’s world through computers in our warm, dry offices. No need to wait for reincarnation! As tracking tools advanced in the last decade, future advances can be foreseen. “Business card” tags now in development will send and receive information, so tagged animals share their data as they pass in the wild, creating swimming data libraries. Tags will soon simultaneously communicate physiology, oceanography, and location.

Smaller tags with better batteries will track smaller organisms and stages of their lives, longer and farther. Underwater GPS, if possible, would expand the types of organisms tracked and applications. These sensors will never fully replace research ships, but they will augment them, especially for poorly known and inaccessible waters of Planet Ocean. The Ocean Tracking Network already tracks tagged animals with an emerging global network of listening stations.

We will continue to work towards a barcoding device similar to the tricorder popularized in the television show Star Trek that we can place in the ocean to scan and identify passing organisms, perhaps if they shed a little DNA or other clues like amino acids. Environmental genetic sequencing, perhaps in tandem with continuous plankton recorders or acoustic and optical sensors with automated recognition software may...
form a sensory package to tell us the global distribution, diversity, and
abundance of species.

Already satellites continuously orbit the Earth, collecting imagery for
myriad applications. Soon, autonomous underwater vehicles (AUVs) may
move across the seafloor like underwater satellites. AUVs today run well-defined, pre-programmed missions, but much as cars on our terrestrial
highways need fuel, the next-generation AUV may visit underwater
docking stations to recharge batteries and download data. Extended
missions could map entire regions without human presence, using acoustic
imaging of larger and larger areas of seabed. Remotely operated vehicles
(ROVs) now have better optics, manipulator arms, and sensors than even
a decade ago, and do many tasks economically that submersibles did in
the past.

With new predictive analyses and models we will sample the ocean
more effectively, placing effort where it will tell us the most. We will
extract important information from noisy and complex data with greater
certainty in our predictions. We can answer more precisely when asked
how much fish can be harvested sustainably, or which ocean regions
should be protected. The many global databases from marine microbes to
mammals captured in OBIS are an enduring Census legacy. Refined
spatial resolution in many physical measurements of the environment is
ripe for overlays of biodiversity knowledge that will tell us much about
diversity, distribution, and abundance of ocean life. Those overlays have
begun, and possibilities are many.

As Census partner programs, the Encyclopedia of Life (EOL) and
World Register of Marine Species (WoRMS) add new species, and
digitization of published work progresses, we will easily confirm names
and characteristics of species by clicking through the Internet to its unique
page. We will view and download photographs and published studies on
that species. A few keystrokes will replace many hours spent in dusty
libraries as graduate students. Funding agencies and scientists will
demand data sharing and integration. Data rescue will add irreplaceable
knowledge and reduce redundant effort. Today with OBIS, we can quickly
see if the sea star we found on the shoreline was seen there before, and
where it occurs globally. OBIS does not include all of the ocean diversity
data ever collected, but as it builds into many millions of records, so does
the utility and potential analyses of the database. Birdwatchers have used
this strategy for years; the search term “birdwatchers’ network” alone
produces over a million hits on Google!

The Census has focused on key areas, but not all ocean life. Groups like
phytoplankton were the focus of previous international science programs.
Some environments such as deep ocean trenches were not sampled.
Contaminants in marine food chains and in water flowing into the ocean were also outside the purview of the first global Census, but are hugely important in a changing ocean. Carcinogens, heavy metals, human hormones, and other pollutants cause change and require bans of seafood consumption. Even deep-sea ecosystems now contain measurable contaminants from human activities. These topics are particularly compelling topics within our expanded view of ocean biodiversity.

The unknowable

The truly unknowable of ocean biodiversity, at least in the immediate future, is very little, except in terms of absolutes. As someone who has studied marine biodiversity my entire career, I find it hard to admit the numbers and identities of all marine species on Planet Ocean may be unknowable. With the tools now available, our capacity to catalog species will continue to accelerate, assuming of course that we can use these tools to overcome the impediment of too few qualified taxonomists and too many species to identify and name. We will eventually know the identities of most species in most environments, the distributions of many species in many environments, and abundances of common species. But the size of the ocean, the remoteness of many habitats, and the limited global scientific capacity will doom some species to remain unknown, perhaps forever. Some of these unknown species will go extinct without us ever
seeing them and others will continue to quietly do whatever it is they do in Planet Ocean.

**Epilogue on an ocean Census**

The Census affirmed that different people need different knowledge about marine life. Those who develop policy want information for their own backyard and in summary form that clearly illustrates pictures of diversity, distribution, and abundance. Managers want to extract living resources like fish and non-living resources like manganese nodules without compromising ocean health. The public wants to know which seafood is harvested sustainably and which regions are hot spots for ocean life and should be protected. Fishermen ask, “Where are the fish?” They want jobs, and if closures cost jobs then decisions must have a sound basis. In short, new research opportunities can produce knowledge for diverse players in ocean use and management. The players range from conservationists to fisheries managers to international organizations such as *International Council for the Exploration of the Sea* (ICES), the *North Pacific Marine Science Organization* (PICES), or the *International Commission for the Conservation of Atlantic Tunas* (ICCAT). All players are part of the translation of scientific discovery to on-the-ground application on and above the seafloor.
Knowledge is power, but just as Lankester’s counter to Huxley’s excessive optimism was overshadowed by the economic needs and politics of that time, new knowledge on ocean life is most powerful when political and societal players act on that knowledge for the long-term benefit of humanity and Planet Ocean. We know much about life in the ocean, and we know a lot of what we do as a hungry society is unsustainable with unpredictable consequences. But change is in the wind. In several well-studied systems, exploitation rates have declined and catch rates have been pushed below a critical threshold that should maintain populations at a healthy and sustainable level. Conservation efforts directed at higher trophic levels have stabilized some populations and allowed others to begin rebuilding. Marine protected areas and closures work in many marine ecosystems, particularly as knowledge gaps that hinder effective design are filled. More tough choices must be made as humanity crowds the ocean.

Though conducted as a 10 year program with a fixed endpoint, another major legacy of this decade of discovery is the creation of research links that will continue the work of the Census into the future. Recently launched national programs such as the Canadian Healthy Oceans Network (CHONe), or programs in India and Korea, will continue ocean biodiversity work beyond 2010, as will international collaborations between and within Census projects where some field efforts will
continue. The Ocean Tracking Network was made possible by the
successes of the Census in tracking organisms and the efforts of Census
Co-Senior Scientist Ron O’Dor. Few of these international programs
would have seen the light of day without the Census. Even without funded
field programs, exchange of specimens, data, and other information will
continue to flow for at least the current generation of scientists. These
programs will work to address questions identified by the Census and
other questions unique to a particular region. The Census has emphasized
sharing ideas and technologies between partners from countries wealthy
and poor. Students have seen a wide range of possibilities and knowledge
gaps of opportunity for future study of marine life.

The age of discovery in the ocean has certainly not passed and more is
discovered that demands preservation. We must do better. Whether a
factory worker in Ontario or yak herder in Tibet has seen the ocean, swam
in its spectacular diversity of life, or dined on its edible riches, they need
to know that every environment on Earth is tied to marine life. We will all
sink or swim together (Figure 10.2). As I look out at the ocean below my
window and type these closing words, I am convinced the enthusiasm for
ocean discovery generated by the Census will carry forward far beyond
2010. We have at least a million reasons and opportunities for wonder,
| 1 | Insert Figure 10.2 here |
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### Table 10.1 Predictions of ocean status in 2020 and beyond.

<table>
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<tr>
<th>Issue</th>
<th>Prediction</th>
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<tbody>
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<td><strong>More crowded</strong></td>
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<tr>
<td>Energy extraction</td>
<td>Drilling deeper onto slopes and further north, more platforms, subsea networks, gas hydrate extraction, wind farms, tidal power, wave energy facilities</td>
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<tr>
<td>Ocean transport</td>
<td>More consumer goods, more oil and more ore, more ocean &quot;highways,&quot; more Indo-Pacific build-up, new Arctic shipping passage, more cruise ships</td>
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<tr>
<td>Population increase</td>
<td>More people, more people on coast</td>
</tr>
<tr>
<td>Communication</td>
<td>More subsea cables for data, power? More Indo-Pacific demand and build-up</td>
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<td><strong>More environmental changes</strong></td>
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<tr>
<td>Coastal concerns</td>
<td>More storms, sea level rise, more nutrients and hypoxia, more pollutants, less ice, changing sediment supply, reduced freshwater supply, more shoreline modification, more lights</td>
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<tr>
<td>Global concerns</td>
<td>More noise, increasingly acidic, warmer ocean, more stratified, more debris, more spills, bigger fishing vessels, better fish finders and bigger nets</td>
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<tr>
<td><strong>More biological changes</strong></td>
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<tr>
<td>Rapid biological change</td>
<td>Fewer wild fish, more aquaculture, more “underutilized” species fished, more modified food webs, more diversity changes, more</td>
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<table>
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<tr>
<th><strong>Unresolved boundaries</strong></th>
<th>Higher stakes (e.g. oil, shipping)</th>
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<tbody>
<tr>
<td><strong>Fewer living resources</strong></td>
<td>More “ownership” of migratory species, more fishing in international waters, more illegal fishing, more piracy</td>
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<tr>
<td><strong>More information</strong></td>
<td>More vessel tracking, more animal tracking, more ocean observatories, more webcams, more floating sensors, more unmanned ocean gliders and other vehicles</td>
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<tr>
<td><strong>Better planning</strong></td>
<td>More information flow (Wiki etc.), more data freely available, better forecasting models (weather, ecological), more public awareness, more marine reserves and protected areas with better design, more species information, better collaboration?, better governance?</td>
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# Census of Marine Life Project List

<table>
<thead>
<tr>
<th>Project Acronym</th>
<th>Study Area</th>
<th>Description</th>
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<tbody>
<tr>
<td>ArcOD</td>
<td>Arctic Ocean</td>
<td>Inventory the fauna of Arctic sea ice, water column, and sea floor</td>
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<tr>
<td>CAML</td>
<td>Antarctic Ocean</td>
<td>Survey life in the Southern Ocean surrounding Antarctica</td>
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<tr>
<td>CeDAMar</td>
<td>Abyssal Plains</td>
<td>Document species diversity in the abyss</td>
</tr>
<tr>
<td>CenSeam</td>
<td>Seamounts</td>
<td>Survey global seamount biodiversity</td>
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<tr>
<td>ChEss</td>
<td>Vents and Seeps</td>
<td>Study deep-water chemosynthetic ecosystems</td>
</tr>
<tr>
<td>CMarZ</td>
<td>Zooplankton</td>
<td>Conduct global zooplankton biodiversity assessment</td>
</tr>
<tr>
<td>COMARGE</td>
<td>Continental Margins</td>
<td>Document biodiversity patterns and habitats of continental slopes</td>
</tr>
<tr>
<td>CReefs</td>
<td>Coral Reefs</td>
<td>Conduct global census of coral reef fauna</td>
</tr>
<tr>
<td>FMAP</td>
<td>Oceans Future</td>
<td>Synthesize changing species patterns</td>
</tr>
<tr>
<td>GoMA</td>
<td>Regional Ecosystems</td>
<td>Document Gulf of Maine biodiversity patterns</td>
</tr>
<tr>
<td>Program</td>
<td>Focus Area</td>
<td>Description</td>
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<tr>
<td>HMAP</td>
<td>Oceans Past</td>
<td>Analyze historical marine animal populations</td>
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<tr>
<td>ICoMM</td>
<td>Microbes</td>
<td>Global study of marine microbes</td>
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<tr>
<td>MAR-ECO</td>
<td>Mid-ocean Ridges</td>
<td>Study macrofauna of northern mid-Atlantic Ocean</td>
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<tr>
<td>NaGISA</td>
<td>Near Shore</td>
<td>Inventory and monitor nearshore biodiversity</td>
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<tr>
<td>OBIS</td>
<td>Information System</td>
<td>Provide web-based global geo-referenced information on marine species</td>
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<tr>
<td>POST</td>
<td>Continental Shelves</td>
<td>Study migration of Pacific salmon</td>
</tr>
<tr>
<td>TOPP</td>
<td>Top Predators</td>
<td>Study migration of large open-ocean animals</td>
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Documenting loss of large trophy fish from the Florida Keys with historical photographs. Conservation Biology, 23: 636–43.


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Figure Captions

**Figure 1.1** The predominance of water on Planet Ocean. Census scientists explored marine life in all realms of the world’s oceans, visualized here on a Blue Marble image.

**Figure 1.2** The diversity of marine life. These images from branches of the evolutionary tree of life illustrate the range of species and forms of life living in Planet Ocean. (a) Giant sulfur bacteria inhabit anoxic sediments, devoid of oxygen, in the South Pacific. Though most bacteria require a microscope to be seen, these giants can be seen with the naked eye. See Chapter 8. (b) *Halicreas minimum*, a jellyfish, drifting as zooplankton as deep as 300 meters. It lacks any stage that attaches to the seafloor. Its fertilized egg changes directly into a larval stage bearing tentacles, which then changes into the small medusa form in the photograph. (c) The prized bluefin tuna, *Thunnus thynnus*, swims in the open sea, hunting sardines, herring, mackerel, squid, and crustaceans. The Census tagged tuna to track their long migrations. See Chapter 7. (d) Shown here is an amphipod, the small crustacean *Eusirus holmii*, that swims through the water as it searches for small prey to seize with its powerful, miniature, claws. (e) In 2009 Census scientists found this flamingo tongue snail, *Cyphoma*
gibbosum, near Grand Cayman, British West Indies. They listed it in the Gulf of Mexico biodiversity inventory amassed by the Census. (f) The bioluminescent lure that anglerfish dangle in front of their mouths attracts potential prey and gives them their name. The ceratoid anglerfish of the genus Lophodolus, found by Census scientists, may be a new species.

**Figure 1.3** The reach of the global Census of Marine Life. The map highlights in yellow more than 80 countries that participated in the Census, encompassing most large coastal nations. Coastal nations in white have limited marine scientific capacity and their coastal waters remain largely unknown, even after the 10 year global effort by the Census.

**Figure 1.4** Seventeen Census projects spanning Planet Ocean. The map locates where Census projects studied marine life, from near shore to mid-ocean, from the Arctic to Antarctica, and from the shallow waters to the deepest ocean.

**Figure 1.5** Spectacular new species. Examples of the thousands of new species discovered by the Census, spanning tiny crustaceans the size of a pinhead to large kelp and lobster, from the shoreline to the abyssal plain. (a) South of Easter Island, Census explorers at hydrothermal vents discovered a crab so unusual it warranted establishing a whole new family, Kiwaidae for a new genus *Kiwa*. Census scientists named the family and genus for the mythological Polynesian goddess of shellfish. Its furry or hairy appearance inspired the *hirsuta* in the second half of its species name, and also its common name, Yeti crab. (b) The small, mostly transparent ghost shrimp, *Vulcanocalliax arutyunovi*, is a new species from the Captain Arutyunov mud volcano in the Gulf of Cadiz. The specimen pictured is an egg-bearing female. See Chapter 8. (c) Even in
shallow water along Alaska's Aleutian Islands, Census researchers discovered new species, such as this kelp, *Aureophycus aleuticus*, which grows 3 meters long. (d) This blind lobster with bizarre claws belongs to the rare genus *Thaumastochelopsis*. The pictured lobster, collected 300 meters deep during a Census expedition, is a new species and it will raise the number of known specimens in this rare genus to five, representing three species. (e) Although the Arctic deep-water copepod crustacean, *Euaugaptilus hyperboreus*, swims weakly, it is classified as plankton, drifting with the current. (f) Scientists found the blue damselfish in 1997 in deep Pacific reefs near Palau. Although its habitat below 100 meters may be short of abyssal depth, they called it *Chromis abyssus* because it lives deeper than most damselfish. *Chromis* describes its striking color. (g) Named by Census scientists for their late colleague Robin Rigby, the octopod *Benthoctopus rigbyae* grows up to 40 centimeters long and lives at depths of 250–600 meters, near the Antarctic Peninsula. (h) Census scientists placed the new species of amphipod or water flea in the genus *Shackletonia*, which honors Antarctic explorer Ernest Shackleton. (i) Lobster fishermen surprised Census scientists in South Africa. The fishermen brought in a spiny lobster caught on Walters Shoals along the Madagascar Ridge, which scientists realized was a new species *Palinurus barbarae*. See Chapter 3. (j) *Lycodonus* sp., a new species of eelpout collected near the Mid-Atlantic Ridge, illustrates that even the familiar fishes continue to yield new species.

**Figure 2.1** Coral reefs, the rainforests of the sea. A large Napoleon wrasse chasing a school of small anthias reef fish swirling above the Elphinstone reef in the Red Sea illustrates the diversity of life in the tropical coastal oceans. The complex structure of coral at the bottom of
the image shelters a riot of hidden species. See Chapter 5. This image was
shot for the Galatée film *Oceans*. See Chapter 4.

**Figure 2.2** Productive kelp forests, filmed without disturbing the
inhabitants. By recycling air exhaled by the divers, the Galatée film team
avoided bubbles that might scare away residents. The divers could also
remain underwater for hours by recycling air. Here, they film in California
kelp forests. The Census included these mid-latitude forests for their
abundant and diverse species. See Chapter 5.

**Figure 2.3** A sampling of ice habitats. Polar ice provides habitat for
some species despite the cold, and the covering ice defines the ocean and
seafloor habitats for those beneath it. See Chapter 6. (a) A scuba diver’s
view of Arctic pack ice in the Canada Basin illustrates how the ice can
block most light, but still transmit scattered beams.
(b) Water fleas, amphipod crustaceans, feeding on algae that grow under
ice near the Beaufort Sea shore. Arctic cod feed on these ice amphipods,
and seals then prey on Arctic cod.

**Figure 2.4** A muddy seafloor, deeper than light. Below 1,000 meters
near Nova Scotia, Canada, this type of seascape on a continental slope is
the most widespread habitat on Planet Ocean and inspired early analogies
to an underwater “desert” long since disproved. See Chapter 8.

**Figure 2.5** An oasis of the deep. Zoarcid fish, or eelpouts, swim over a
community of tubeworms, *Riftia pachyptila*, on an East Pacific
hydrothermal vent. The huge biomass of tubeworms and other species
near hydrothermal vents contrasts starkly with the sparse biomass in
muddy sediments under much of the deep sea. These abundances earned hydrothermal vents their nickname of “underwater oases.”

Figure 3.1  Sampling Planet Ocean. To explore and sample Planet Ocean, scientists lowered bottles, nets, and grabs over the rails of ships to collect water and sediments, or bring back specimens. Later, scientists visited the deep ocean in person or launched vehicles they could drive from afar to collect samples. (a) The recovery of a conductivity–temperature–depth (CTD) sampling rosette from the Beaufort Sea to study waters of the western Arctic. Niskin bottles surrounding the CTD close at defined depths to collect water for nutrient and microbial analysis aboard ships. See Chapter 7. (b) A box corer lowered over the rail of a ship samples sediments on the seafloor beneath coastal and deep-sea waters. See Chapters 5 and 8. The metal spade on the left side of the sampler swings down after the metal box penetrates the seafloor, sealing the sample inside for transport to the surface. (c) A pair of bongo nets towed behind a ship to collect two samples at once of zooplankton and larval fish. See Chapter 7.  (d) Three explorers dive in ALVIN, the world’s best-known deep-ocean submersible, which descends as deep as 4,500 meters (almost 3 miles), accessing two thirds of the global seafloor. ALVIN has explored the deep seafloor, including hydrothermal vents (Chapter 8), photographed the sunken Titanic, and helped recover a lost hydrogen bomb. (e) ROPOS, a Canadian remotely operated vehicle (ROV), sends video along a tether to pilots and scientists aboard a surface ship as the ROV samples down to 2,500 meters. (f) Testing REMUS 6000, an autonomous underwater vehicle (AUV) at the dock in Woods Hole, Massachusetts. AUVs are untethered and sent off on programmed missions, such as mapping hydrothermal vents. See Chapter 8. REMUS recently searched the deep Atlantic for wreckage of an Air France flight.
Figure 3.2  Anatomical and genetic analysis, sharp eyes, and international collaboration solve a long-standing conundrum. After scientists had classified each of these three fishes as different families, more detailed morphological analysis and new specimens revealed that they are actually larvae, males, and females of a single family of whalefishes, the Cetomimidae. This revelation illustrates how even relatively well-studied fishes continue to yield exciting surprises.

Figure 3.3  How many more species remain to be found? Estimating unknown marine diversity is a tricky business. A theoretical curve illustrates that if nothing changes as time passes, more species are discovered and described, year by year. This theory applies to one group or species or to all the species in one environment. If the curve begins to level off (lower curve), then statistical models can estimate when the number of species will stop rising, indicating that all the species in a given group or given environment have been discovered. But if the curve shows no signs of leveling off (middle and upper curves), then discovery will continue, making it impossible to know which of those two curves will eventually form as knowledge of new species accumulates.

Figure 4.1  Acoustic technology counts fish. Acoustic technology aboard a ship instantly imaged a school of fish the size of Manhattan. Acoustic waves remotely sensed a shoal of more than 20 million fish, almost certainly herring, off the coast of New Jersey. The white lines show depth contours, and the colors show fish abundance. In about a minute, this new technology images hundreds of cubic kilometers of ocean, expediting efforts to census how many fish are in the sea. Sound waves sent from a source on one ship bounce off of fish, which are
counted by a receiver hanging over the side of a second ship. See Chapter 5.

**Figure 4.2** Tagged animals make oceanographic observations from an animal’s perspective. The range of tags now available potentially allow scientists to eventually track three quarters of the fishes and mammal species as they swim around Planet Ocean. Smart tags also measure depth, temperature, and light. As they swim and dive, elephant seals, for example, collect temperature observations in the Southern Ocean. The tag on the head of the female southern elephant seal pictured on Livingston Island, Antarctica, stores observations on her environment for scientists to read later.

**Figure 4.3** The Ocean Biogeographic Information System (OBIS) makes information accessible. OBIS unites the Census, providing a universally accessible database about ocean life. Since 2000, OBIS has grown to 22 million records from more than 700 different databases integrated into one. The map shows the global distribution of OBIS data records, with a color scale ranging from blue dots for few to red for many records, thus highlighting locations of sampling strengths and gaps.

**Figure 4.4** Visualization makes the information public. The Census is part of Google Earth. There, any viewer of the Ocean layer can find Census pages for some of its newly discovered species, such as the ghost shrimp shown here, and other information on ocean life.

**Figure 4.5** Genetics reveals the evolutionary connections of life in Planet Ocean. Genetic barcode groupings of life show sharp edges for some groups and closer relationships for others. The image shows vector
analysis “Klee diagrams” used by the Census. Red and yellow show species are more closely related to each other than to distant blue species. See Chapter 7.

Figure 5.1 The ocean rim. The drawing illustrates different coastal habitats studied by the Census (see Chapter 5) from the tropics near the equator up to temperate environments at mid-latitudes. Each habitat has unique characteristics and its own suite of species.

Figure 5.2 Tools for sampling life on the ocean rim. The collage shows some tools that Census scientists used to sample coastal waters. (a) Census researchers on an Antarctic ice floe tag seals with the newest generation of biologgers. (b) Laying out PVC quadrats that define intertidal plots to be sampled in the Gulf of Maine, the late Robin Rigby, shown in the photograph, coordinated sampling. (c) A light attracts animals for examination in an aquarium on Lizard Island Reef, Australia. (d) A scuba diver deploys Artificial Reef Monitoring Structures (ARMS), “condos” made of PVC, that mimic a reef. Small holes and gaps in the plastic ARMS provide homes for corals, crabs, and mollusks. Metal stakes secure the ARMS to a reef for a year or two until scientists retrieve the condos to see what types of life colonized them.

Figure 5.3 Diverse ocean rim habitats. From the tropics to the poles and from the intertidal to the subtidal, the ocean rim provides a variety of habitats. (a) In shallow water, the sea star *Solaster*, the sea anemone *Tealia*, and sea urchins live on rocks in the rocky seashore of eastern Canada. Because these species mostly live in shallow water on rocky bottoms, scientists can study them easily. (b) A coral reef, the Banco Chinchorro in Mexico, is home for the blue chromis, *Chromis cyanea*, and
other fish. Reefs are rich in species. (c) In sand, a giant guitarfish, *Rhynchobatus djiddensis*, also known as white-spotted guitarfish, whitespot ray, sandshark, and whitespot shovelnose ray, lies hidden off Lizard Island, Queensland, Australia. (d) A rocky outcrop in shallow water off eastern Canada protects an American lobster, *Homarus americanus*, and provides home for attached invertebrates. Lobster now comprises the most important fishery in Eastern Canada and the northeast United States. (e) Seaweed grows on seafloor exposed at low tide around Knight Island in Prince William Sound, Alaska. When low tide exposes intertidal life, Census scientists need only rubber boots to access their sample plots.

**Figure 5.4** The known and unknown from the small to the large.

Although the polychaetes, mollusks, and crustaceans near 1 millimeter in size are the best known among the small creatures, many species of that size are still unknown. Still smaller life, teeming forms that can only be identified by genetic analysis, are easily overlooked altogether. There may be millions of viruses, archaea, and bacteria. In the upper figure (a) scientists know some groups well (blue), monitor a small subset of this biodiversity (orange), and attempt to manage an even smaller subset (orange hatched). The lower figure (b) enlarges the part of the upper figure (a) that illustrates the larger organisms, most of which are known.

**Figure 5.5** Life on the ocean rim. The species that inhabit the ocean rim range from kelps to sharks, from the tropics to mid-latitudes to the poles described in Chapter 6. (a) A cerianthid anemone off eastern Canada catches small particles from water flowing past its tentacles. (b) A white-topped coral crab from a dead coral head off Heron Island, Australia. (c) A whale shark, *Rhincodon typus*, photographed on Ningaloo Reef,
Australia. (d) An Arctic *Solaster* sea star photographed in Alaskan shallow waters. (e) *Nereocystis*, the bull kelp, lives in shallow water off the Pacific coast of North America. (f) An octopus collected at a depth of about 10 meters off Lizard Island, Australia with ARMS (Autonomous Reef Monitoring Structure).

**Figure 6.1** Spectacular polar life near the surface down to the seafloor. Everywhere they looked at the poles, north and south, scientists found life. (a) The shell-less pteropod or swimming snail, *Clione limacina*, grows as long as 4 centimeters in both Arctic and Antarctic waters, and in waters in between. (b) The comb jelly, *Aulacoctena* sp., collected with a remotely operated vehicle (ROV) in the deep Arctic Canada Basin. (c) An Arctic sea star collected with an ROV on the deep-sea floor of the far northern Canada Basin. (d) The ribbon worm nemertean, *Pelagonemertes rollestoni*, hunts for zooplankton prey, which it harpoons with a dart attached to the tongue coiled within it. Its yellow stomach reaches out to feed all parts of the body. Census scientists photographed this 3 centimeter long specimen during an Antarctic expedition. (e) The sea spider, *Austropallene cornigera*, abounds in Antarctic waters. (f) A juvenile, deep-sea octopus, *Thaumeledone gunteri* found in Antarctic waters.

**Figure 6.2** Ice defines habitats at the ends of the Earth. This drawing shows the special characteristics of polar ecosystems. Near the poles, ice reaching out from coasts defines seasons and thus defines changes in food and habitat. The inset illustrates the differences between the Arctic Ocean, surrounded by land, and the Southern Ocean, surrounding Antarctic land.

**Figure 6.3** The Antarctic species incubator. Visualization of how
different species of octopus evolved from Antarctic ancestors and moved northward, some farther than others. The red line on the inset shows that some species of Antarctic octopus crossed the tropics and reached far into the Northern Hemisphere, all the way to Greenland and Alaskan waters.

**Figure 6.4** Habitats at the ends of the Earth. Though not especially diverse, the span from ice-covered surface down to the deep seafloor encompasses an array of polar habitats that support their own suites of species. (a) On the ice in the Arctic Canada Basin, a polar bear mother and her cub. (b) Below the Arctic ice, ice amphipods feed on algae attached to ice crystals. (c) In the Antarctic Larsen B region, deep-water corals grow in abundance at 120 meters depth. (d) Under pack ice, Arctic cod feed on amphipods and other ice fauna. (e) In the Antarctic, ice fish adapted to cold have no hemoglobin or red blood cells, which makes their blood thinner so it pumps more easily and saves energy. (f) Along Alaska’s Aleutian Archipelago, *Ptychodactis* sp., a new species of “swimming” anemone. They detach from the hard substrate, inflate, and drift with currents over the seafloor to attach elsewhere.

**Figure 7.1** Ocean life in motion is defined by their waters. This drawing shows pelagic ecosystems of Planet Ocean, where differences in light, temperature, salinity, and nutrients determine productivity. Productivity in turn limits who can live there.

**Figure 7.2** The complexity of ocean motion. Satellite images of chlorophyll and temperature trace flowing surface waters off eastern North America. (a) This satellite false-color image of the Gulf Stream shows phytoplankton traveling curved highways and circular gyres in the water. The photosynthesis in phytoplankton feeds all marine life – except
the peculiar communities near vents and seeps. In the photograph, red
color shows abundant phytoplankton in productive water and the blue and
purple color shows the sparse phytoplankton in unproductive water. (b)
This second satellite image of the Gulf Stream shows a false-color image
of surface temperatures. The water temperature indicated by colors in the
image traces movements of Planet Ocean and visualizes the array of
watery habitats.

Figure 7.3  Ocean drifters. Plankton shown here range from microbes
measuring far less than the width of a human hair out to jellyfish almost as
long as a baseball bat. (a) *Protoperidinium pellucidum*, a colorized image
of a protist dinoflagellate. (b) Microbes from the Pacific Ocean off
Southern California, stained to fluoresce. The numerous faint dots are
viruses, and the brighter and less numerous medium dots are bacteria or
archaea. The central object or dot is a photosynthetic protist with brightly
stained nucleus. (c) “Squidworm,” an extraordinary worm found off
Southeast Asia during a Census cruise by US and Filipino researchers and
photographed by a *National Geographic* photographer. (d) A
bioluminescent jellyfish, *Aequorea macrodactyla*, photographed during a
Census expedition to the Celebes Sea. (e) *Neocalanus robustior*, an
abundant Arctic copepod that eats phytoplankton, are key prey for fish. (f)
The predatory *Rhizophysa* resembles a sprite dancing in the night sea. A
diver captured it in the mid-Atlantic for DNA barcoding. This relative of
the Man-o’-War shown in three views measures 10 centimeters long, but
its stinging tentacles stretch 50 to 60 centimeters, when fishing for food in
shallow water.

Figure 7.4  Checkpoints listen for migrants. The Census arrayed lines of
acoustic receivers on the bottom of rivers and along the Pacific
continental shelf. As tagged fish with radio transmitters pass between receivers, they are identified and counted. (a) A map of Census receivers along the Pacific coast of North America. (b) A Census acoustic receiver displayed in Vancouver Aquarium’s Strait of Georgia exhibit. Submerged receivers at “choke points” along the coast count and identify tagged fish as they pass by. (c) How an array of receivers “listens” for passing fish, whose tags emit radio waves (gray waves) that are detected by receivers (yellow) and relayed to a nearby ship.

Figure 7.5  Seabirds enjoy endless summers. The routes of sooty shearwaters from colonies in New Zealand extend from the Southern Ocean to the Bering Sea as they migrate between hemispheres to enjoy endless summers. The map traces 19 birds during breeding (light blue) and subsequent migration. Yellow identifies the start of northward migration, and orange identifies the end of southward migration for wintering.

Figure 8.1  Deeper than light. A diversity of life, from tiny crustaceans to rare fish, lives in the dark deep sea. (a) Abyssochrysidae are a family of rare tropical snails that live in deep water. Like most deep-sea species, the Abyssochrysidae are smaller than their relatives that live in shallow water. (b) The swimming sea cucumber, *Enypniastes*, differs from its sluggish relatives that spend their lives crawling along the seafloor. (c) A new species of squat lobster photographed on the seafloor near Southwest Australia. The Census produced a new catalog of squat lobsters around the world. (d) An undescribed copepod, collected at 5,000 meters in the Southern Atlantic Ocean. Copepods usually dominate the drifting zooplankton and compete for the title of largest animal biomass on Earth. Copepods worldwide feed fish, whales, seabirds and other crustaceans
such as krill. (e) Caught at 2,000 to 2,500 meters, the bizarre, elongated orange eel, *Neocyema*, is only the fifth specimen of this species ever caught and the first for the Mid-Atlantic Ridge. (f) The jewelled squid, *Histiotethis bonnellii*, swims above the Mid-Atlantic Ridge at depths from 500 to 2,000 meters.

**Figure 8.2** Into the deep. The drawing shows the array of specialized habitats on the seafloor, thousands of meters below the surface. The Census standardized datasets to enable comparisons among these specialized habitats.

**Figure 8.3** Deep-sea habitats. Habitats in the deep sea span productive vents and seeps, complex cobbles and seamounts, and rolling plains of sediment. (a) A deep-water coral habitat on the upper continental slope of Nova Scotia, Canada. Sampling this region of the discovery corridor was part of the Canadian Healthy Oceans Network (CHONe) that grew from the Census. The Network explores deep-water habitats from coral areas like this one, as well as exploring life in deep-sea sediments. (b) Seeping natural gas from the seafloor fuels a microbial reef 250 meters beneath the northwest Black Sea. This community is fed by specialized microbes that use natural gas rather than photosynthesis, which fuels most biological communities. (c) Census scientists sailed on the Australian icebreaker *Aurora Australis* to explore diverse deep-water coral near Antarctica, 725 meters below the surface. (d) Around cold seeps, tubeworms may live singly or aggregate in fields of thousands, exploiting methane and sulfides bubbling from the seafloor. Some of the species gather around hydrothermal vents, too, but many live only near the cold seeps. (e) In deep water near the Larsen B area of Antarctica, abundant deep sea cucumbers all turn to feed in the same direction. Relatives of sea stars, sea
cucumbers help cycle the carbon in food through deep-sea ecosystems. (f) An aggregation of brittlestars on the Macquarie Ridge off New Zealand extend their arms to catch food in passing currents.

**Figure 8.4** The explored and unexplored ocean. The number of OBIS samples in five zones of the ocean, labeled A–E, shows the dearth of samples between 2,000 and 6,000 meters deep in the water and on the deep seafloor. The horizontal axis splits the ocean into depth zones (A = 0–200 meters, B = 200–1000 meters, C = 1000–4000 meters, D = 4000–6000 meters and E = >6000 meters), where the width of each zone is proportional to global surface area. The number of data records in each cell is standardized to the volume of water in that cell and log_{10}-transformed. The inset shows in greater detail the continental shelf and slope, where the most records are found.

**Figure 8.5** Long ocean ridges divide vast abyssal plains on the seafloor. The distinct mid-ocean ridges on the seafloor demarcate some edges of the plates that cover the Earth. During geological time, the slow-moving plates rearrange the seafloor.

**Figure 8.6** More garbage than life on the seafloor. Searching for marine life, Census researchers towed a trawl at 3,000 meters beneath the Eastern Mediterranean near Crete. Instead of living creatures, they hauled up a net filled with trash. Passing ships and currents had carried and deposited the trash, which decayed little on the deep seafloor.

**Figure 8.7** Sampling in the deep. Census scientists lowered samplers, dove down in submersibles, or launched autonomous vehicles to explore the deep. (a) Wood Hole Oceanographic Institution’s Autonomous
Benthic Explorer (ABE). ABE was lost off the coast of Chile in March 2010 after 16 years of service exploring the global ocean. (b) Submersible *Nautille* carried French explorers down to study life on the seafloor around hot and toxic hydrothermal vents. (c) Acoustic multibeam sonar map of a seamount atop the Macquarie Ridge. The ridge extends 1,400 kilometers southwest of New Zealand into the Southern Ocean. The image, magnified fivefold in the vertical dimension, will guide future sampling. (d) Near a vent 3 kilometers beneath the equatorial Atlantic, Census researchers used the remotely operated vehicle *Quest* to find shrimp and other marine life. (e) A multi-corer is lowered over the rail of CGS *Hudson* to the seafloor thousands of meters below to collect sediments and their fauna with minimal disturbance.

**Figure 9.1** A jetty of molluscs past. Middens of queen conch (*Strombus gigas*) date from 1200 to 1500 AD on La Pelona Island, Los Roques Archipelago, Venezuela, forming a jetty. The size of the shell jetty shows the importance of mollusks to humans in that era.

**Figure 9.2** Small boy, big cod. Today fisherman can rarely catch cod like this 25 kilogram prize caught near Battle Harbour, Labrador, just north of the island of Newfoundland, in the early 1900s.

**Figure 9.3** Life lost. The total abundance of major groups of marine life declined by 10 to 60% in 12 estuaries and coastal seas around the world since human arrival. SAV refers to submerged aquatic vegetation. See Chapter 9.
Figure 9.4 Abundant North Sea bluefin tuna in oceans past. Northern bluefin tuna, *Thunnus thynnus*, for sale in the fish auction hall at Skagen, Denmark, about 1946. Today, their numbers are much diminished.

Figure 9.5 Diminishing trophies. Changes in the size and species of trophy fish caught on Key West illustrate that humans have altered marine life in only a few decades. The diminution of the trophy fish on charter boats from (a) 1957 to (b) early 1980s to (c) 2007 dramatizes the loss.

Figure 10.1 Hot spots of ocean diversity can now be located. Global datasets encompassing Planet Ocean now locate the highest diversity. Hurlbert’s index of diversity tells how many different species are found in a random sample of 50 individuals from 5° x 5° squares in the ocean. In the figure, red indicates high species diversity, blue low. In the white areas, the dataset did not contain the required minimum 50 specimens to calculate the index.

Figure 10.2 Hope for Planet Ocean. A skin diver quietly accompanies a sunfish, *Mola mola*, swimming through Pacific water. Human and fish illustrate the beauty and coexistence of humanity and marine life. The Census has shown that marine life can be resilient. Where the human affinity for marine life causes its protection, it can recover.
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