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 provides information that will enable us to manage resources more effectively, conserve diversity, reverse habitat losses, and respond to global climate change.

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For Fred – Scholar, mentor, friend

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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.[1] 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 Moon. 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,*

[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.

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 CO_2 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 CO_2 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 2,700 researchers in 500+ research expeditions, added over a thousand new species to science (and counting), put together nearly 28 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 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 many transmitted data through satellite, allowing the tracking of animal movement across the ocean. This enabled the identification of "hot spots," "cold spots," "highways," and "truck stops" 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 into 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 Project (POST) 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 can contain 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 similar techniques to those championed by CMarZ and ICoMM, polar microbiologists discovered 1,500 kinds of Arctic *bacteria* and 700 kinds of *archaea*. CAML has added over 11,000 barcode sequences for Antarctic species from their collections. The Census is working with the Marine Barcode of Life (MarBOL) 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 Reef 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 Animal 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

[2] 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.

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: "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 (. . .) The next generation AUVs may visit underwater docking stations to recharge batteries and download 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 2000–2010 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

PREFACE

The Census of Marine Life has been the opportunity of a lifetime to travel the world and meet wonderful scientists who each bring their own passion, toolbox, and diverse view of the ocean. The Census is about the thousands of scientists who have bounced around on ships, slogged through samples, and spent countless hours hunched over their computers trying to bring clarity to an opaque ocean. The project leaders have kindly shared stories, manuscripts, imagery, and ideas that are the core of this book. Their work builds on that of many other talented scientists around the world.

The goal of this book is to bring the excitement of the Census and its findings to as broad an audience as possible. This book encompasses many hundreds of science papers, but to improve readability, I simply include a list of those by chapter rather than within the chapter text itself. An online "educators" version of the book, available through Cambridge University Press (www.cambridge.org/9781107000131), includes reference citations within the text so anyone interested can link specific information to its source.

The task of trying to corral many different Census activities into coherent outputs has been a collective adventure with the Census Synthesis Group that I chair, which includes Jesse Ausubel, Darlene Trew Crist, Michele DuRand, Fred Grassle, Pat Halpin, Sara Hickox, Patricia Miloslavich, Ron O'Dor, Myriam Sibuet, Edward Vanden Berghe, Boris Worm, and Kristen Yarincik. Generous funding from the Alfred P. Sloan Foundation allowed us to focus on ideas and outputs that span this book and beyond to capture different aspects of the Census. We have benefited enormously from working with the Census Scientific Steering Committee led first by Fred Grassle

and then by Ian Poiner. The Secretariat managed by Kristen Yarincik has done a spectacular job orchestrating everything Census.

The hospitality of Heidi Sosik, Judy McDowell, and the Biology Department at Woods Hole Oceanographic Institution created a great opportunity to research much of this book. That time was made possible by the support and flexibility of my colleagues at Memorial University, Ian Fleming, Paul Marino, Garth Fletcher and Mark Abrahams. The Canadian Healthy Oceans Network team most especially Joan Atkinson, made a confluence of opportunities work, and covered for me when needed.

My graduate students in Newfoundland were wonderfully patient and helpful in their spare time, particularly Krista Baker who did an outstanding job formatting the many references that Ashlee Lillis helped hunt down. Ryan Stanley kept the lab afloat in my absence.

Feedback and ideas on early chapters from Ron O'Dor, Patricia Miloslavich, and Darlene Trew Crist helped to set the tone for the book. Reviews by Michael Sinclair, Serge Garcia, Vera Alexander, and an editorial "haircut" by Jesse Ausubel and Paul Waggoner greatly improved the content. Excellent support from the Mapping and Visualization Team led by Pat Halpin and the Education and Outreach Team led by Sara Hickox were critical in producing the figures and imagery in this book, often at short notice. Frank Baker's efforts to secure photo credits were also a tremendous help.

Michele DuRand was invaluable, spending many hours proofing, editing, and advising. Darlene Trew Crist provided tremendous counsel on many important details. The patience and flexibility of Martin Griffiths and Lynette Talbot at Cambridge University Press helped greatly.

Family members lent much support and humor, most importantly the companionship and encouragement of my wife along this long voyage of discovery.