OCEANOGRAPHY AND MARINE BIOLOGY SERIES

SEAS AND OCEANS SET

# Ecosystem Sustainability and Global Change

Edited by

André Monaco and Patrick Prouzet

iSTE

WILEY

Ecosystem Sustainability and Global Change

From the ***Seas and Oceans*** Set
coordinated by
André Mariotti and Jean-Charles Pomerol

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# Contents

# Foreword

We have been asked by ISTE to stimulate work in the area of the environment. Therefore, we are proud to present the “Seas and Oceans” set of books, edited by André Monaco and Patrick Prouzet.

Both the content and the organization of this collection have largely been inspired by the reflection, initiatives and prospective works of a wide variety of national, European and international organizations in the field of the environment.

The “oceanographic” community, in France and internationally – which is recognized for the academic quality of the work it produces, and is determined that its research should be founded on a solid effort in the area of training and knowledge dissemination – was quick to respond to our call, and now offers this set of books, compiled under the skilled supervision of the two editing authors.

Within this community, there is a consensus about the need to promote an interdisciplinary “science of systems” – specifically in reference to the Earth’s own “system” – in an all-encompassing approach, with the aim of providing answers about the planet’s state, the way it works and the threats it faces, before going on to construct scenarios and lay down the elementary foundations needed for long-term, sustainable environment management, and for societies to adapt as required. This approach facilitates the shift of attention from this fundamental science of systems (based on the analysis of the processes at play, and the way in which they interact at all levels and between all the constituent parts making up the global system) to a "public" type of science, which is finalizable and participative, open to decision-makers, managers and all those who are interested in the future of our planet.

In this community, terms such as "vulnerability", "adaptation" and "sustainability" are commonly employed. We speak of various concepts, approaches or technologies, such as the value of ecosystems, heritage, "green" technologies, "blue" chemistry and renewable energies. Another foray into the field of civilian science lies in the adaptation of research to scales which are compatible with the societal, economic and legal issues, from global to regional to local.

All these aspects contribute to an in-depth understanding of the concept of an ecosystemic approach, the aim of which is the sustainable usage of natural resources, without affecting the quality, the structure or the function of the ecosystems involved. This concept is akin to the "socio-ecosystem approach" as defined by the Millennium Assessment (http://millenniumassessment.org).

In this context, where the complexity of natural systems is compounded with the complexity of societies, it has been difficult (if only because of how specialized the experts are in fairly reduced fields) to take into account the whole of the terrestrial system. Hence, in this editorial domain, the works in the "Seas and Oceans" set are limited to fluid envelopes and their interfaces. In that context, "sea" must be understood in the generic sense, as a general definition of bodies of salt water, as an environment. This includes epicontinental seas, semi-enclosed seas, enclosed seas, or coastal lakes, all of which are home to significant biodiversity and are highly susceptible to environmental impacts. "Ocean", on the other hand, denotes the environmental system, which has a crucial impact on the physical and biological operation of the terrestrial system – particularly in terms of climate regulation, but also in terms of the enormous reservoir of resources they constitute, covering 71% of the planet's surface, with a volume of 1,370 million $km^3$ of water.

This set of books covers all of these areas, examined from various aspects by specialists in the field: biological, physical or chemical function, biodiversity, vulnerability to climatic impacts, various uses, etc. The systemic approach and the emphasis placed on the available resources will guide readers to aspects of value-creation, governance and public policy. The long-term observation techniques used, new techniques and modeling are also taken into account; they are indispensable tools for the understanding of the dynamics and the integral functioning of the systems.

Finally, treatises will be included which are devoted to methodological or technical aspects.

The project thus conceived has been well received by numerous scientists renowned for their expertise. They belong to a wide variety of French national and international organizations, focusing on the environment.

These experts deserve our heartfelt thanks for committing to this effort in terms of putting their knowledge across and making it accessible, thus providing current students with the fundaments of knowledge which will help open the door to the broad range of careers that the area of the environment holds. These books are also addressed to a wider audience, including local or national governors, players in the decision-making authorities, or indeed "ordinary" citizens looking to be informed by the most authoritative sources.

Our warmest thanks go to André Monaco and Patrick Prouzet for their devotion and perseverance in service of the success of this enterprise.

Finally, we must thank the CNRS and Ifremer for the interest they have shown in this collection and for their financial aid, and we are very grateful to the numerous universities and other organizations which, through their researchers and engineers, have made the results of their reflections and activities available to this instructional corpus.

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# 1

# Ocean, Biodiversity and Resources

## 1.1. The history of life in the oceans

The Earth was formed 4,600 million years ago. From ancestral geodiversity originating from prebiotic chemistry, which gave rise to the set of chain reactions that produced the first structured sugar, nitrogen base and amino-acid molecules, “life” appeared in oceans, fairly quickly after the initial cooling and condensation of water, over 3,800 million years ago.

Duve [DUV 96], 1974 Nobel Prize Laureate, said, in *Dust of life* in 1996, that Earth was so ideally positioned with respect to the Sun that it would not be possible for life not to appear (i.e. it was bound to), while J. Monod referred to it as an improbable occurrence. The oldest known sedimentary rocks (Akilia Island, in South Greenland) containing carbon of biological origin date back 3,850 million years. We must imagine very primitive life at the start, based on a world of ribonucleicacid (RNA) and protocells [MAU 03]. Current deposits of stromatolite (rocks that precipitate bicarbonate), with very rich deposits in Australia, are very precious since, in their silicified parts, they contain the most ancient known fossils of microorganisms: cyanobacteria. These began their conquest of the oceans around 3,400–3,200 million years ago, at the time without any atmospheric oxygen. In the presence of water, photosynthesis produces oxygen and sugars from light and carbon dioxide ($CO_2$) due to specific pigments

Chapter written by Gilles BOEUF.

in the cells; this process began to take place on Earth around 3,500 million years ago. Oxygen started to diffuse beyond the confines of the aquatic environment around 3,200 million years ago; the current composition of the atmosphere, with its 21% of oxygen, dates back at around 100 million years, in the Cretaceous Era.

In this ancestral ocean, events occurred that were of critical importance both for the living world in general and for biodiversity:

– the appearance of the nuclear membrane and the individualized nucleus (prokaryote-eukaryote transition) around 2,200 million years ago;

– the capture of ambient cyanobacteria that would become symbionts and the organelles of the cell – mitochondria and plastids, with desoxyribonucleicacid (DNA) of their own – respectively, around 2,100 and 4,100 years ago;

– the appearance of multicellular organisms and metazoans around 2,100 million years ago.

Another exceptional occurrence took place in this ancestral ocean: the appearance of sexuality, first with prokaryotes, and later also with eukaryotes, which would prove to be essential for the explosion of biodiversity. Sexual reproduction allows for genetic mixing, which creates originality and unprecedented diversity: all individuals are different. A population endowed with sexuality evolves much more quickly. Furthermore, the prevalence of sexuality facilitates the development of an “arms race” between parasites and their hosts (coevolution and molecular dialogue [COM 01]), as genetic mixing ultimately leads to quicker “neutralization” of the parasite, and sexual selection that is clearly different to natural selection [DIM 05].

The exit of organized metazoan life from the oceans took place after the Cambrian explosion (570 million years ago), where the first plant life-forms (first vascular plants in the late Silurian, around 415 million years ago, with moss existing long before that) and terrestrial animal life-forms (arthropods and vertebrates, among others) would leave traces on the continents (myriapods, scorpions, later lungfish, rhipidistia and *Ichthyostega*, around 440 million years ago). Numerous new adaptations were developed, both by plants and animals; the transit to terrestrial life and air-breathing represent an exceptional occurrence in the history of life. The differences are fundamentally between aquatic and terrestrial animals. The former extract their oxygen from water through diffusion to the heart of the organism for small species, or through gills for larger ones. A volume of seawater at equilibrium with the air contains around 30 times less oxygen than the same volume of air. Anisosmotic aquatic breathers (whose internal environment is different to the surrounding water – e.g. fish) cannot develop too large an exchange surface (gills) due to the dangers inherent to the physical consequences of osmotic "flows" (water and electrolytes), with the animal losing water to the sea, or being "flooded" by river water. In fact, a fish is constantly subject to a difficult compromise, between developing a maximum gill surface, to capture the oxygen in an oxygen-poor and very changeable environment, and a minimum surface to help prevent serious water–mineral imbalances. Aquatic animals excrete ammonia and, for the vast majority, do not thermoregulate. By contrast, terrestrial animals must endure ultra violet (UV) rays, dehydration, a very different experience of gravity (consequently, requiring a much heavier and resistive skeleton and muscle mass), and must use excretion products that are not highly toxic or are non-toxic (such as, uric acid or urea). Much later, in the Triassic period, around 210 million years ago, after the third great species extinction crisis, the premises of thermoregulation were developed, and used to maximum efficiency first by large dinosaurs, and then mostly by birds and mammals. A very good example of the return to the ocean is the case of cetaceans, which began this reacclimatization to marine life based on the primitive terrestrial forms of artiodactyls (for example, hippopotami) similar to *Diacodexis*, and then amphibian forms (like the *Pakicetus* or *Ambulocetus*) around 55–50 million years ago, whose current giant forms (the largest animals to have populated the planet since the origins of life, which humans have been uncaringly massacring for 160 years) are very recent. Today, 12 *phyla* are exclusively marine animals and have never left the ocean (echinoderms, brachiopods, chaetnognaths, etc. – see Table 1.1). However, only two exclusively terrestrial groups (not *phyla*) exist: myriapods and amphibians. Additionally, the seas contain vast quantities of biomass: the bacteria in the subsurface layer of the ocean alone represent 10% of all carbonated biomass on the planet [PAR 94]. The marine environment has, therefore, played a decisive role in the history of life, and today the ocean continues to play a crucial role in the evolution of life and climate [BOE 08].

Today, we are searching for traces of “extraterrestrial” life, by concentrating efforts on DNA, amino-acids, Adenosine triphosphate (ATP), etc., without forgetting that the key molecule of life is water. The make-up of every living being contains water – ranging from a few percent, in the case of the “driest” organisms (e.g. plant seeds), to over 95%, for certain aquatic species (algae, jellyfish, ascidia, among others). The human body itself is made of two thirds of water; a human baby at birth has 75% of water and our brain has more than 80%. Water is life [BOE 12]: for example, take the borders of a Chilean desert which, every 10–12 years when it rains, becomes covered with flowers (along with vast numbers of insects) in the space of a few days, lasting a few weeks, and then “returns” to years of extreme aridity. This is natural; however, humans can also trigger explosions of life by irrigating the desert.

The departure from water was, therefore, a truly decisive event in the history of life. The ocean has been salty (essentially with sodium chloride) for a very long time, and today we are able to understand this stability in its salinity: the billions of tons of cations (calcium, potassium, magnesium, sodium, etc.) brought to the sea by the rivers since they began flowing, are compensated for: in the case of calcium, by the trapping of marine sediments and the formation of limestone; for potassium by the absorption of clay (see Chapter 4 in [MON 14a] and Chapter 2. Magnesium and sodium are retained in the oceanic ridges (serpentinization and clay-formation from pyroxenes and olivines). Serpentinization corresponds to the hydration of minerals, and alteration into clay corresponds to the deterioration into small grains of less than 2 μ in diameter. For anions, bicarbonates are constantly mixing with the atmosphere and biosphere, and for chlorides, which do not enter into any major biogeochemical cycles, we currently believe that chlorine was one of the original volatile elements that was dissolved in seawater initially and remained there (not much is carried by rivers today). This current salinity, of around 35 psu (internationally recognized “practical salinity unit”, corresponding to 35 g of sodium chloride per liter) causes osmolarity (meaning "osmotic pressure") of 1,050 milliosmoles per liter ($mOsm.l^{-1}$).

Marine life has always had to cope with this, and has developed a universal strategy of intercellular isosmotic regulation for which the vast majority (of animals only) of invertebrates and certain vertebrates have the same osmotic pressure (internal environment and cells) as that of seawater. Another strategy, which has arisen in certain crustaceans, referred to as extracellular anisosmotic regulation, has allowed for great migration capabilities and the ability to change environments, by maintaining the osmotic pressure of cells and body fluids within a very small range (between 300 and 400 $mOsm.l^{-1}$; humans are at 302); regardless of the external salinity. In fact, in this latter case, we can "die of dehydration" in seawater; the presence of salts causing outakes of water from the organism to the external environment through exchange surfaces in close contact (blood–water) with salt water, such as the epithelium of the mouth and gills (with seawater salts migrating in the opposite direction). Marine osmoregulators (for example, boned fish) have had to establish strategies for the constant intake of seawater and the evacuation of salts through the gill, with the kidney proving to be incapable of fulfilling this function on its own. One of the main problems posed by terrestrial life is the conservation of water and the struggle against dehydration [BOE 12]. The role of the kidney is, therefore, essential: think of the small kangaroo rat from the desert, which never has access to drinking water and produces urine that is nine times more salty than seawater. For its part, "terrestrial" biodiversity would develop later on, after the establishment of specific mechanisms, and took off massively in the Carboniferous Era, from 345 million years BC onward.

We will, therefore, take inspiration from certain aspects related to life in the ocean: first its age and its often much simpler organization, and second its productivity and specific diversity:

– Which renewable living resources will humans be able to take from the ocean (fishing and aquaculture)?

– Which molecules of interest will we extract from marine organisms?

– Which marine models will be pertinent for a basic scientific approach or the resolution of fundamental questions in the field of biomedicine?

## 1.2. Specifics of marine biodiversity

Marine biodiversity is a very special case [BOE 11]. The recognized diversity of species in the oceans accounts for no more than 13% of the set of living species currently known: i.e. less than 250,000. There may be two reasons for this. The first is that our knowledge – especially of deepwater areas and microorganisms, bacteria and microalgae – is still only very incomplete (so we considerably underestimate the biodiversity of the oceans). New methods, such as coupling between flow cytometry (a technique that entails launching particles, molecules and cells at high speeds through a laser beam in order to characterize them) and molecular probes (which reveal an organism with specific features), are currently discovering a totally unforeseen, extraordinary level of biodiversity. “Sequencing the ocean” (C. Venter, sequencing all the DNA in a given volume of filtered seawater) moves in the same direction; the data obtained appear, for the most part, to be revelations. The recent round-the-world expedition *Tara Océans* has also produced exceptional data. For all prokaryotes and very small eukaryotes, recent molecular approaches (sequencing of 16S and 18S ribosomal RNA, among others) produce astonishing results daily. Furthermore, and this is the second reason, it is also obvious that marine ecosystems and the way of life in a continuous environment (by the dispersion of gametes and larval stages) of the species that populate it, are less predisposed to strict endemism (the notion of living exclusively here and nowhere else) than in terrestrial habitats. There are many more barriers and segregations favorable for speciation (the evolutionary process by which new living species arise) on land than in the sea. This leads to significant differences in terms of specific diversity; marine ecological niches do not achieve the richness of terrestrial ones, which are much more fragmented and are more favorable to new species. The stability of the open ocean in deep waters, over at least the past 100 million years, is also extraordinary: in terms of pH, osmotic pressure and salinity, temperature, hydrostatic pressure linked to depth, dissolved gas content, etc. The closer we are to the coast, the more this fluctuates. Human activity is changing this; we will revisit this point later on. This stability is less prone to give rise to new species. Consequently, marine biomasses can be considerable, and the performance of phytoplankton alone, with its capacity for self-regeneration, accounts for over 50% of the planet's productivity.

| Phylum | Genus or species | Pelagic | Benthic |
|---|---|---|---|
| *Placozoa* | *Trichoplax adhaerens*, very small flat animals, base form of invertebrates, 3 sp | | X |
| *Ctenophora* | From 1 mm to 1.5 m, *Pleurobrachia*, *Beroida*, *Cestum*, *Velamen*… Burgess shale, 190 sp | X | |
| *Xenoturbellida* | Two known species, *Xenoturlla westbladi*, very small "marine worms" discovered in Scandinavia | | X |
| *Cycliophora* | Microscopic animals transported by cold water lobsters, *Symbion*, two species | | |
| *Mesozoa* | 165 sp, small marine invertebrate parasites, *Rhombozoa* and *Orthonectida* | | |
| *Sipuncula* | Sipunuculid worms, *Sipunculus vulgaris*, since the Cambrian, non-segmented, 1,284 sp | | X |
| *Echiurians* | *Metabonellia*, *Bonellia*, *Prometor*… "marine worms", 234 sp | | X |
| *Phoronidians* | *Phoronis*, *Phoronopsis*, etc., live in a cyclindrical tube, 31 sp | | X |
| *Brachiopods* | With a lophophore, a crown of tentacles and a shell, 12,000 known fossils, 441 sp today | | X |
| *Echinodermata* | Starfish, sea urchins, crinoids, sea cucumbers, etc. > 14,000 sp | X | X |
| *Chaetognatha* | *Arrow worms*, 120 species in 20 genus, *Spadella*, 280 sp | X | X |
| *Hemichordata* | Marine deutorostomes in the form of "worms", graptolite fossils, *Saccoglossus*, 143 sp | | X |
| *Cephalochordata sub-phylum* | Amphioxus, *Branchiostoma lanceolatum*, *Assymetron*, 25 sp | | X |
| *Tunicata sub-phylum* | *Urochordata*, Ascidies, 3,000 sp in four classes, *Styela*, *Didemnum*, *Salpida*, *Appendicularia*, etc. | | X |

**Table 1.1.** *Exclusively marine phyla (according to [BOE 11])*

This table is simply indicative of exclusively marine groups. How do we then chose them? *Cephalochordata* and tunicates are *sub-phyla* of *Chordata* (which have continental taxons), the *Kinorhynca*, *Priapulida* and *Loricifera* have been grouped within the *Cephalorhyncha* with the *Nematomorpha*, which are terrestrial; *Xenoturbellida*, *Cycliophora* and *Mesozoa* can be considered as valid *phyla*.

There are five to seven more terrestrial taxons today, compared to oceans, which is worthy of inquiry since initially life was exclusively marine, before the various great departures from the oceans, at different locations in different forms, 440 million years ago, for "developed" metazoans. The great Permian-Trias extinction played a primordial role with 96% of the extinction of species both marine and continental around 252 million years BC. The explosion of flower plant species, of insects and many other groups on Earth, around 130–110 million years ago, was decisive after the initial radiations (explosion in the number of species deriving from a single ancestral one) starting from the Carboniferous period. The coevolution between plants and pollinators, and the appearance of an infinite number of new niches, have often been proposed to explain the acceleration of speciation in continental environments of this era [BOE 11, BOY 10]. It is also evident that dispersion phenomena of reproductive products and larvae in the oceans played an important role in the distribution of current species and biogeography. Endemism is notably considerably more limited in the ocean, the stability in deep water and the continuity of this gigantic environment explaining this. If it is not rare to find living species over a few $km^2$ on land, then we do not know of any examples of such confined species in the sea. The large variety of methods of reproduction in the sea also draws from dispersion phenomena in water bodies, with males and females not constrained to being in close proximity. Thus, do connectivity and the much weaker variations in environmental factors create the great stability in the ocean at large and the particularly specific characteristics of the biodiversity that it houses? Coastal systems, intermediaries with strong land-related influences, are subject to much greater variations.

Finally, we must not forget that biodiversity is much more than just specific diversity, which includes both species and their relative abundance. The meaning of the word "biodiversity" has been interpreted in many ways but generally expresses the "genetic information which contains each elementary unit of diversity, be it an individual, a species or a population". This determines its history, past, present and future. Even then, this history is determined by processes that are also components of biodiversity. In fact, today we group different approaches under this term together:

– the study of fundamental biological mechanisms that explain the diversity of species and their specific features and that require us to further study the mechanisms of speciation and evolution;

– the most recent and promising approaches in the field of functional ecology and biocomplexity, including the study of material and energy flows and the great biogeochemical cycles;

– the utility of nature as goods and services for mankind in their capacity to provide food, high-value substances for medicines, cosmetic products, etc., molecular probes or even obtaining ancient ancestral and original models for fundamental and finalized research, in order to resolve agronomical or biomedical questions;

– the establishment of conservation strategies for preserving and maintaining a natural inheritance consisting of a naturally expected heritage by/for future generations. We must also particularly insist on the fact that inventories and descriptive lists are not sufficient to specify what the biodiversity is: much more important are the relations established by the living beings between each other and their environment.

## 1.3. Renewable living resources

Humans have been fishing since ancient times, certainly tens of thousands of years. As soon as they reached shores, they began to collect shells, algae, etc. As in agriculture and continental environments, humans have been farming certain marine species on the coasts for at least 4,000 years (Egypt, China, etc.). The use of renewable living resources being very well outlined elsewhere in this work and in