OCEANOGRAPHY AND MARINE BIOLOGY SERIES

SEAS AND OCEANS SET

# Vulnerability of Coastal Ecosystems and Adaptation

Edited by
André Monaco and Patrick Prouzet

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coordinated by
André Mariotti and Jean-Charles Pomerol

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# 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 longterm, 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

# Marine Ecosystems under Toxic Pressure

## 1.1. Introduction

In terms of the pressures of anthropogenic origin to which marine ecosystems are subjected, the ideas that spring to mind are intensive fishing, indirect forms of destruction, the destruction of habitats – by fishing equipment during the exploitation of the deep sea, the development of ports – eutrophication, plastic macrowaste, etc. On the subject of toxic pressure, we can also mention the incidents of accidental pollution, of which the explosion of the oil-rig Deepwater Horizon, in the Gulf of Mexico in February 2013, recently gave us a sad example, or even, chemical shipwrecks, such as that of the Ievoli Sun in October 2000.

These events are indeed particularly striking because of the extent of the immediate mortalities that they cause, which are generally short-lived. However, the toxic pressures that marine ecosystems undergo due to the chronic and ubiquitous contamination of the environment by multiple contaminants are less well known and understood by the general public.

The first research on metallic trace elements in marine environments dates from the 1970s, and belongs mostly to the studies of geochemists, searching to understand the global cycle of the elements of the Earth’s crust, including some toxic metals, such as mercury, lead and cadmium and other essential metals, such as zinc and copper (see the reference work *Tracers in the Sea* by Broeclker and Peng [BRO 82]). Nevertheless, the goal, above all, is then to arrive at a precise knowledge of the quantity of these metals in seawater, which contains so little of them that handling them carries high chances of contamination… These metals are not, therefore, being studied as toxic pollutants. The emergence of ecotoxicology (the term was coined for the first time by René Truhaut in 1969) will very gradually lead to an understanding at least of the local effects in the sea, when accidents occur, or indeed in the vicinity of pollutant refuse. However, it was only with the application of the 1996 law on water that treatment plants emptying waste into the sea saw themselves obliged to control their emissions. Until then, it was thought that the oceans' power to dilute waste was sufficient protection. Finally, more recently, developments in analytical environmental and organic chemistry allowed the detection, in all environments, of organic xenobiotic[1] substances with toxic effects. Environmental chemists and ecologists became aware of the fact that the ocean, the environment where terrestrial life originated (see Chapter 1 of [MON 14c] also from the Seas and Ocean set of books), but which mankind does not inhabit, had nevertheless absorbed manmade chemical emissions and that marine ecosystems were living with this chronic pressure.

Since then, the major challenge facing scientists has been to understand how marine ecosystems behave under toxic pressure, what evolutions and adaptations this pressure causes, and at what cost (metabolic, phenotypic and genetic). In effect, other major pressures are being exerted, among them climate change and acidification of the oceans, etc. (see [MON 14a, b and c] also from the Seas and Oceans set). And the future of the entire biosphere is directly linked to the oceans' capacity to sustain significant primary production, trapping atmospheric carbon dioxide, which is the basis whole of the trophic oceanic chain, which feeds not only the sea birds… but also people.

First, these are the details of the ocean environment that are affected *vis-à-vis* the toxic pressure. Then, the biological responses will be described at the level of individuals exposed to toxic pressure, independent of each another ("direct effects"). Finally, the focus turns to the group of effects known as "indirect effects", that is to say, those that affect the relationships between the individuals of which an ecosystem is composed. Little is yet known about these indirect effects, but initial observations have tended to show that they are the primary impact; understanding the behavior of these systems under toxic pressure has to be taken into account.

# 1.2. Details of the marine environment

All aquatic environments are subject to pollution of anthropogenic origin, and all the associated ecosystems are subject to the toxic stress that results. The ocean, because of its dimensions – it is the most vast of the biosphere's ecosystems (1.4 billion km$^3$) whose depth reaches, on average 3,800 m – and because of its distance from the continents appears relatively protected in comparison to rivers and lakes. Rivers and lakes are often very directly impacted by human use: runoff from agricultural land or soil that has been made impermeable, sources of diverse phytosanitary products, hydrocarbons, dioxins, metals, etc.; they are the recipients of more or less well-treated collection networks, sources of molecules from pharmaceutical synthesis, cosmetics, detergents, products from eroded materials, etc.; outlets, finally, of the widespread contamination of our environment by extremely varied products (see also Chapters 2 and 3). Locally, the impacts of these contaminations can be very pronounced (for example [DED 09], chemosphere), even if they are difficult to prove, because of the mobility of flowing water [FEC 14] and the physico-chemical variability of these environments: diurnal variations in pH and temperature, seasonal variations in organic matter and in shade from forest cover, regional variations in the concentration of eroded minerals, etc., all are modulating factors in the bioavailability of the contaminants [TUS 07].

Assessment of the contamination of the marine environment – which is vast, chemically and thermically stable, and relatively homogeneous in the oceanic areas – and of the consequences for the associated ecosystems is, therefore, fundamentally different. In fact, it is important to distinguish coastal environments from open oceanic environments, situated beyond the continental plateau. The risks of contamination in the coastal zone, to which estuaries and laguna can be added, are fairly similar to those of continental environments, down to a few specific details.

### 1.2.1. *The coastal zone*

This interface between the continent and oceans is home to specific ecosystems where important transfers of matter, energy and genes occur. The marshes, the seasonal nature of rivers’ hydrology and the pre-eminence of primary production confer on the coastal zone a physico-chemical instability analogous to that of continental waters. The biodiversity housed by coastal regions is adapted to the strong variability in the characteristics of these transition environments, but its resilience has been broken down by anthropic impacts, leading to an increased vulnerability to pollution and global change, even more critical in the case of islands and lagoons. The recipient of nutritive salts eroded or washed from continents, the coastal and littoral zone, which is not very deep, provides numerous services to ecosystems (support and regulation especially) via primary production, the recycling of major elements, the metabolization of contaminants or their export into sediments and hydrological regulation. Costanza *et al*. [COS 97] estimate that a third of the global benefits and services to ecosystems are formed there. Because of this, but also due to the access to waterways that they provide, as well as the attraction that they exercise for our contemporaries, coastal areas concentrate 60% of the world's population – which is becoming increasingly urban and concentrated in megacities – at least 100 km from the coasts.

Coastal ecosystems, rich and vulnerable by nature, are therefore subject not only to pressures provoked by global changes, including climate change, but also to pressures due to this very strong concentration of continental activities as well as maritime activities. The species exploited (fishing, conchiliculture (the farming of shellfish), the farming of sea vegetation, etc.) are also subject to these pressures, which could explain certain recurrent weaknesses in the immune system (F. Akcha, personal communication). Moreover, exposure to pollutants can lead to a contamination of the biomass, rendering it unfit for human consumption [LEB 06].

Once they have passed through the filters of lagoons, deltas and estuaries, in which the levels of salinity trigger a significant precipitation of matter, trapping certain components (cadmium in the Gironde or in the Bay of the Seine, for example, among the most well-known instances [SHI 13]), a proportion of the collection of micropollutants issuing from the drainage basin are found in the coastal zone (hydrocarbons, pesticides, metals, persistent organic products, medication, cosmetics, etc.). For example, the supplies of hydrocarbons to the marine environment account for 80% of the telluric supplies, accidental pollution, therefore, only represents a small fraction, of which the impact is mainly local and often significant for macrofauna. At the end of the 1980s, the development of chromatography in liquid form for environmental research, coupled with mass spectrometry at high resolution, enabled hydrophilic molecules of pharmaceutical, cosmetic or hygienic origin to be gradually detected, at weak concentrations that qualify as emergent. Pioneering studies have enabled the identification of a number of these substances active in rivers, lakes and aquifers (for example, in the United States [KOL 02]). In France, the first studies on coastal waters and estuaries were only carried out quite recently [CAS 06]. Antibiotic and anti-inflammatory products, fungicides, antidepressants, analgesics and anticancer medications have been identified, of which it is still difficult to evaluate the real impact on fauna and aquatic flora. More specifically, the use of the coast leads locally to strong concentrations of cosmetic sun protection products, oils and perfumes, as well as products used to protect the hulls of boats from biological fouling (copper, tributyltin (TBT) and its replacements). For example, at only 20 $ng.L^{-1}$, TBT considerably disrupts the growing metabolism of mussels. At 2 $ng.L^{-1}$, TBT, an endocrine disruptor, is capable of modifying the sex of certain marine gastropods (masculinization of the females by the effect called imposex) [ABI 12]. Nanoparticles of titanium oxide, used in a lot of sun protection products, are part of the emerging concerns. Nevertheless, in their review on the subject, [KLA 09] do not report any more observations *in situ*. Research is currently concentrated on the evaluation *in vitro* of the potential effects of these nanoparticles on coastal organisms [CAN 10]. Finally, the coastal zone permits active exchanges between the column of water and the sediments, which unfortunately often constitute a significant reservoir of persistent contaminants. Much like continental lakes, the toxic threat associated with them thus lasts decades, being reactivated following the reshaping of the sediment or modifications of its “redox status”.

## 1.2.2. *The open ocean*

The risks from contamination of the open ocean by toxic substances are different. There is less biodiversity there, which results from the low habitat fragmentation of the environments, and from their relative homogeneity. Nevertheless, marine ecosystems are of the greatest importance for mankind: for their supply of protein biomass (15% of the total supply) and for their value to local communities: the cradle of life on Earth, still largely unexplored, is believed by some to be outside the reach of anthropogenic pressures [GOU 12, p. 18]. They are home to wild species of great longevity, at the top of the trophic chain.

One way of taking account of the immensity of the oceans and their inertia consists of evaluating the residence time of elements in their different compartments. This amount, homogeneous for a time, is obtained by dividing the volume of a reservoir by the fluxes that cross it, under the hypothesis of stationarity. The residence time of water in the global ocean is in the order of 3,000 years [DE 09]. For the Mediterranean, it is, for example, a hundred years. This means that an easily biodegradable contaminant, carried from the continent, such as glyphosate (in the order of a month in water, INERIS, 2010), will not be found again in a significant concentration in the whole of the Mediterranean basin. However, persistent organic contaminants, such as PolyChlorinated Biphenyls (PCB), can easily be dispersed. In effect, the duration of the half-life in water (suggested by [MAC 92] to be two years for tri- and tetra-chlorides, and six years for penta- to hepta-chlorides) does not include transfers in the food chain, one of the most efficient methods of storage and transport for hydrophobic substances. Chlordecone, a chlorine insecticide used to combat the banana-tree weevil in the Antilles, is one of the contaminants for which it is still difficult to suggest a typical biodegradation time. In fact, the risks for the open ocean, where ecotoxicology is concerned, are on the one hand those of persistent contaminants on the scale of oceanic fluxes (a decade and more), and on the other hand of substances whose planetary cycle is in part controlled by specific marine processes. Mercury can be counted among the latter, of which the atmospheric supplies through snow, then the arrival at the ice interface of sea and seawater appears to be primordial [COS 11, DAS 14], but whose planetary cycle remains to be elucidated.

These compounds are generally hydrophobic – this is what makes them difficult to biodegrade in an aquatic environment – and lipophilic, and they, therefore, spread in the trophic chain in spite of the fairly weak concentrations that cause them to be diluted in the ocean. Their enduring presence, associated with this particular mode of transfer, leads large sea predators to become contaminated, whether these are, for example, tuna [KRA 03], mammals or even birds [DIE 13]. The risks are, therefore, both the chronic toxicity of these substances for large organisms and the ecosystems to which they belong – which for a long time were thought to be unable to carry pollution of human origin – as well as the fitness of the human foodstuffs that are taken from them. This concern is even more important when a population’s food supply is mainly taken from marine sources, as is the case, for example, for the Inuit [DAL 13] and Polynesians [DEW 08].

### **Box 1.1**. *The chemical universe and the environment*

More than 37 million chemical substances are currently listed in the world, for the most part substances resulting from biosynthesis. Around 100,000 chemical substances are produced, imported and used on the European market, and 5,000 of them (5%) are considered to be dangerous for mankind and the environment. Sources of contamination by metals are multiple and include mining activity, the steel industry, transport, the use of different types of batteries and the painting and dying industries, as well as the use of phosphorous fertilizer (cadmium). Taking account of the diversity of the molecules, the study of organic contaminants represents a very important undertaking. Very schematically, it is possible to distinguish four main substance groups:

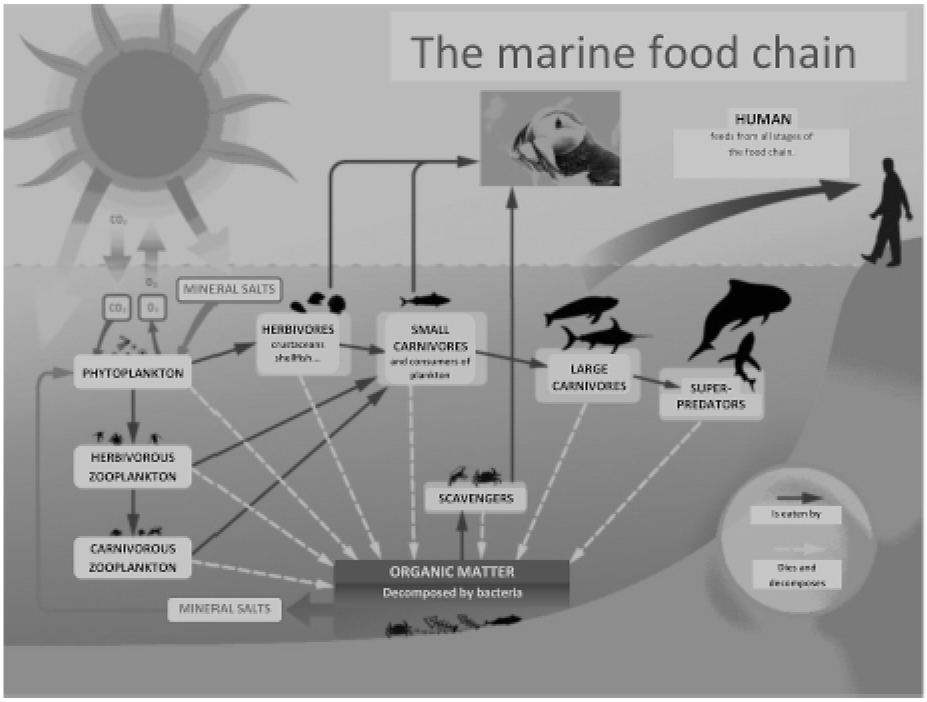
– hydrocarbons, of which aromatic polycyclic hydrocarbons (APHs) are the most worrying for aquatic environments;

– pesticides, with some 900 types in current use and a usage rate of 80,000 tons applied each year;

– biocides, which refers to substances used in a non-phytopharmaceutic context, such as additives included in anti-fouling paints for use at sea, which cause non-negligible contamination by different organometallic (TBT) or organic (diuron or atrazine such as Irgarol 1057) or active metallic substances (copper);

– other organic synthetic substances that represent a large number of substances (chlorinated solvents, PCB, flame retardants, phthalates, detergents, colorants, etc.). The selection criteria for chemical contaminants judged to be a priority for the environment are based on three properties: persistence (P) defining persistent substances in the environment (for example, persistent organic pollutants (POPs) such as DichloroDiphenylTrichloroethane (DDT)), bioaccumulation (B) defining their capacity to accumulate in organisms and toxicity (T). These three properties define a group of substances that are called PBT substances. To this group should be added substances that have carcinogenic and mutagenic properties and effects on the reproductive system that are called CMR substances. Endocrine disruptors are also associated with this group.

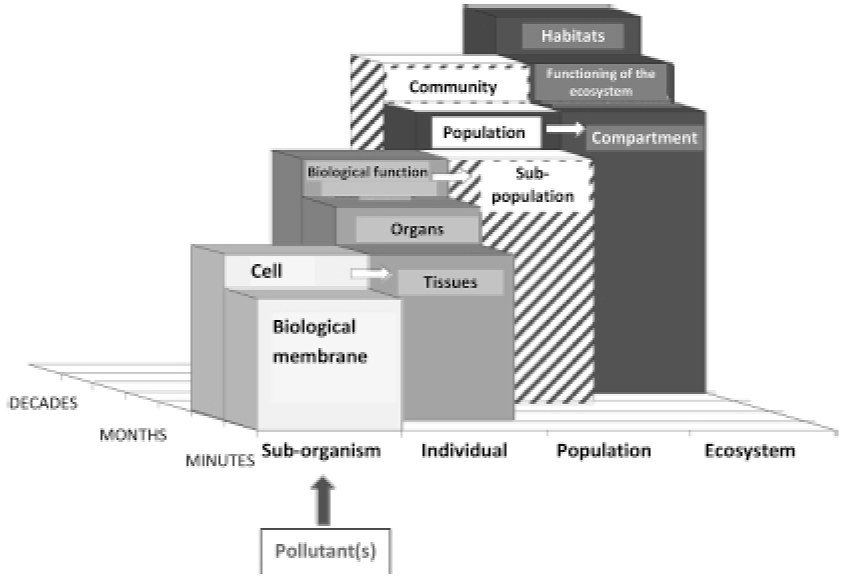
**Figure 1.1.** *Example of the marine trophic chain*



# 1.3. What is the biological response of organisms to contaminants?

The absorption of a contaminant by a living organism triggers a disruption in its metabolism. This disruption leads to a biological response, which results either in the cell returning to its non-disturbed state or in a manifestation of toxic effects. An organism’s biological response to a toxin can be seen as the result of the interaction between the intrinsic properties of the substance and those of the organism exposed to it. It depends on the chemical properties of the contaminant (structure, activity and mode of action) and the physiological, biological and ecological properties that characterize the organism at the moment in its life when it is exposed to this contaminant. It is also variable within a single species and a single age group, depending on individuals. For example, many of us are exposed to the flu virus each winter, and only some will actually become ill. Its general physiological state has, in effect, an impact on the reaction of an organism in the face of a stressor. Each species, and each individual within a species, therefore shows a specific response to each chemical product. Moreover, the environment in which this species evolves and its connection with other parts of the ecosystem will also condition its response. Finally, the direct impact of contaminants on a species and/or a subsection of it can generate indirect effects on the entirety of the ecosystem, as we will see later (Figure 1.2).

**Figure 1.2.** *Adaptation of the schematic representation of the field of ecotoxicology studies depending on the level of complexity of the lifeform and the time, from [MUN 95] and [ADA 00]*



## 1.3.1. *At cellular level*

The manifestation of a disturbance in the functioning of the cell is the result of interaction between the cellular biomolecules and contaminants. This interaction is very specific: its occurrence and intensity depend on the organism’s physiology at the moment it is exposed and on the toxic product’s mode of action.

#### 1.3.1.1. *General remarks on the modes of action*

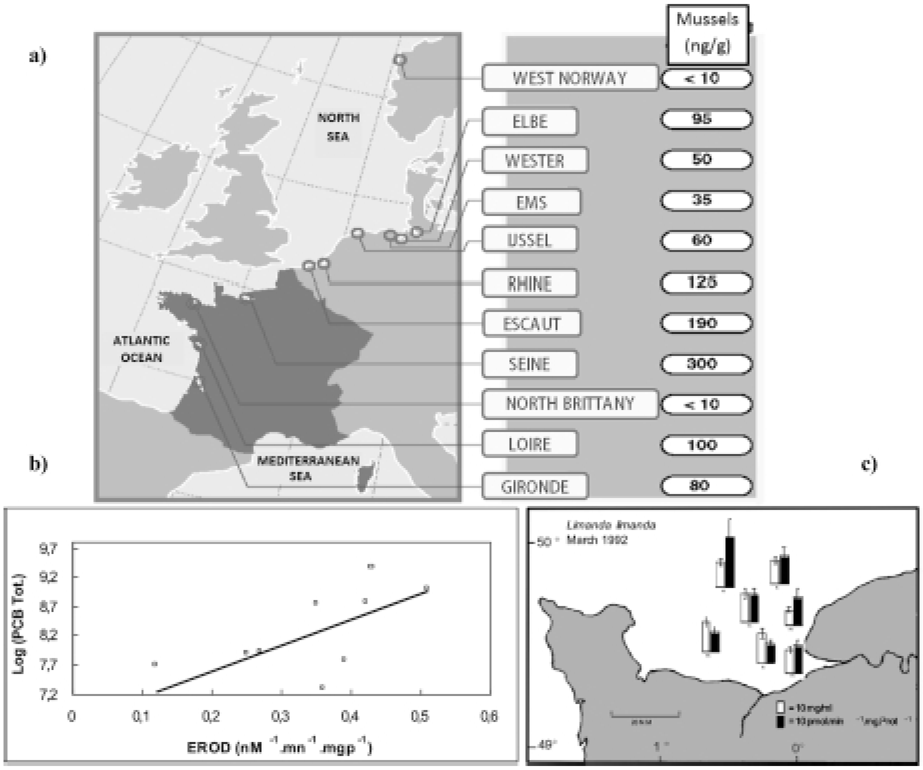
The contaminant’s mode of action is determined by its chemical structure [ESC 02, PAK 00, TRE 04]. Pollutants have been classified into four categories, on the basis of their structure/activity ratios (SARs) [HER 89]. The “inert” products (class I) and “slightly reactive” products (class II) have a narcotic action: they react in a non-selective manner with biological membranes, thus modifying their structure and functioning. Their effect depends mainly on their hydrophobia [VAN 92]. The “reactive” compounds (class III) and the compounds “with a specific mode of action” (class IV) react selectively or not at all with the cellular biomolecules. Once in the cell, they are generally hydroxylated and eventually combined with other molecules in order to be eliminated. However, the combinations are sometimes more toxic than the initial substance.

For a family of contaminants with a given mode of action, the cell’s response depends on the presence and the abundance of the product’s targets and on its metabolic capacities, as well as on its ability to repair damage [ESC 02]. These physiological properties characterize species. For example, the active elimination of the contaminant by cells calls upon different metabolic paths whose biomolecules are unequally distributed between different species [BAZ 97, CAL 83, IBR 98] or within the same species. Thus, a given cell’s membership of a taxonomic group determines its response to a given product.

### 1.3.1.2. *The cellular response: the means of identifying exposure to contaminants before the event*

The impact of pollutants on a subcellular level can lead to the inhibition and/or triggering of diverse proteins and enzymes implicated in the metabolism and the excretion of xenobiotics. These detoxification mechanisms allow organisms to maintain themselves in the fact of exposure to pollutants. Modulations of biotransformation enzymes have, therefore, been the subject of a very large number of investigations over the last 30 years, notably among fish [AND 92, GOK 98, WHY 00]. Much effort has, in particular, been devoted to the identification of biomarkers of detoxification, that is to say proteins, or indeed enzymes, whose activity levels reveal the starting of processes within the cell. This work focuses on the measurement of cytochrome protein levels P450 (phases 1A and 3A) [MUR 97, WEB 02], the measurement of ethoxyresorufin-O-deethylase activity (EROD) [GOK 98, TEL 04, WHY 00] or the enzymes from the glutathione-S-transferase family [GEO 94, KIM 10, VAR 89]. As an example, Figure 1.3 shows a correlation between levels of contamination and EROD activity [BUR 94, GAL 91]. These molecular biomarkers are not, however, specific to the contaminants that trigger their activation, and their responses are potentially affected by biotic or abiotic factors.

**Figure 1.3.** *a) Contamination in mussels (ng.g*$^{-1}$*) on European coasts by PCB from measurements in RNO 1991; b) correlation between EROD activity (nMol produced by enzymatic activity (resorufin), per minute and per mg of liver protein) and level of contamination in PCB (ng.g*$^{-1}$*) in samples of plaice [GAL 91] and c) EROD activity (by the same units as (b)) in samples of flounder in the Bay of the Seine [BUR 94]*



# 1.3.2. *On an individual level*

Disturbance in cellular physiology generally manifests itself by the effects on the survival, growth, reproduction and indeed the behavior of individuals. It is also at an individual level that contamination occurs. This does not depend only on the chemical form of the contaminants, from which it has wrongly been thought possible to define “the” bioavailability

[GOU 13], but above all on the specific details of an individual’s life history.

#### 1.3.2.1. *How specific and individual variability influences contamination*

The biological and ecological characteristics of individuals are implicated at all stages of the contamination process and the biological response: exposure, absorption, elimination and eventual compensation for the product’s effects. In the first place, the duration of contact between the organism and contaminated environment depends on the number and duration of the developmental stages undergone during the lifecycle, as well as the presence of defense mechanisms over the course of this cycle [SPR 05]. The habitat and feeding method determine the organism’s behavior and influence its level of exposure [KOI 92].

The biological and ecological characteristics of species are moreover involved in the kinetics of the organism’s contamination [ESC 02]. In effect, the speed at which a contaminant is absorbed depends on the intensity of the exchanges between the organism and its environment. This absorption speed can be described using food assimilation rates [CAN 02] and the exchange surface between the organism and environment. This exchange surface is generally represented by the ratio between the surface of the body and its volume (S/V) [ESC 02]. In this ratio, assessment of the body surface takes account of the toxin’s different absorption routes: the integument, the digestive tract and the respiratory surfaces [WEI 04]. For two organisms of similar size, the higher the S/V ratio, the more rapid the kinetics of the toxin’s absorption [KOI 92]. In practice, it is, therefore, mainly the mode of feeding and the respiratory system (gills or integument) that is involved in the organism’s contamination kinetics.

### 1.3.2.2. *How specific variability and individual influence the depuration rate*

The biological and ecological characteristics of species and individuals are also involved in their capacity to eliminate or store the contaminant in a non-dangerous form. Passive elimination of the compound implies its excretion or accumulation in inert compartments of the organism [GRO 99]. Furthermore, tissues with a high lipid content offer a significant storage volume of hydrophobic contaminants. Differences in the presence and volume of these compartments generate a strong interspecies variability in biological response to toxins and, in particular, to organic products [ESC 02]. These differences are linked to the relative size of species: in effect, it is generally the largest organisms that possess the most lipidic reserves [CAN 02, ESC 02].

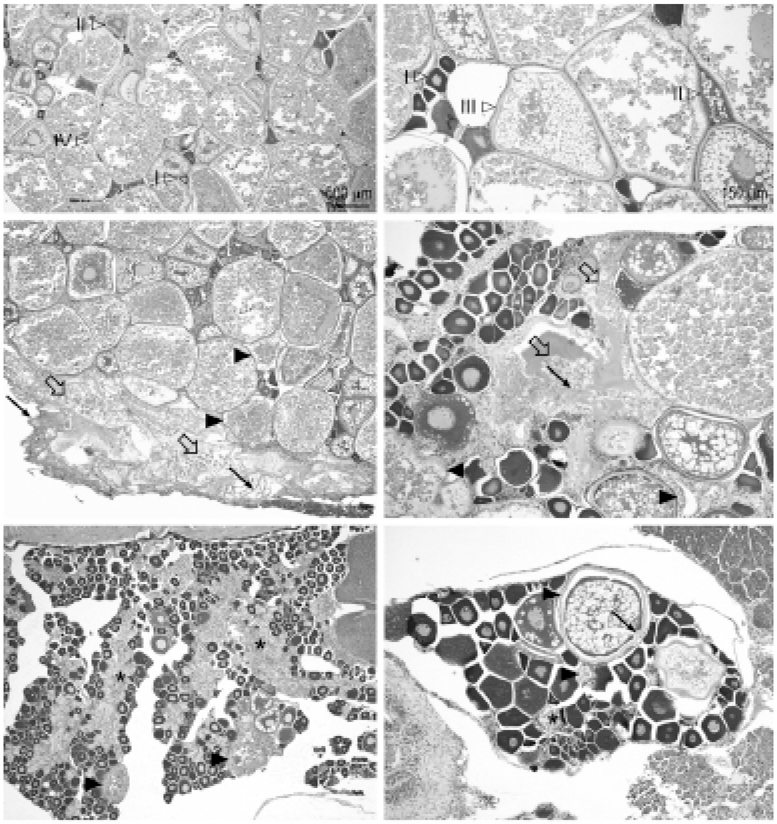
Thus, it is mainly the characteristics linked to use of the habitat and food, as much as the characteristics linked to the pattern of the organisms' life history, which determines their response to contaminants at an individual level.

### 1.3.2.3. *Some types of toxic effects*

Certain pollutants, characterized as "endocrine disruptors" (PE), act on organisms' hormonal equilibrium. Endocrine disruptors are exogenous substances that trigger effects harmful to the health of an organism or its descendents, following changes to endocrine function. The action mechanisms of PEs are multiple, since they can act on all the stages of endocrine regulation, from the synthesis of hormones to activity at the level of the target tissues. Among aquatic organisms, exposure to PEs has been associated with harmful effects on the reproduction (Figure 1.4; [CRA 08, DAO 11, MEN 08, MIL 05]) of individuals and populations. Certain pollutants have also been identified as neurotoxic, leading to effects on the neural functions of fish, and they can, therefore, potentially affect the species's behavior and learning [PEA 13].

Diverse chemical agents have the capacity to interact with the DNA molecule and to modify its nature [CAJ 03, HEB 96]. Types of damage to DNA are generally separated into two categories: genetic lesions (functional lesions) caused by mutagenous agents and chromosomic lesions (structural lesions) caused by clastogenic agents [EVE 94, LIV 00, MAR 10].

**Figure 1.4.** *Histological structure of the ovaries of female zebra fish (taken from [DAO 11])*



COMMENTARY ON FIGURE 1.4.– The different stages of maturity of ovarian follicles (I–IV) can be identified in the ovary of a control fish. The fish ovary exposed to PCBs (at levels in the order of those encountered in the Loire estuary;

photo, center) shows a number of atretic (arrow) follicles. The number of follicles at stage III (vitellogenous) and stage IV (mature ovocite) is slightly diminished in comparison to those of the control. The ovaries of fish exposed to elevated concentrations of PCB (Seine estuary; photo below) show an almost total absence of follicular stages III and IV, which makes reproduction impossible.

### 1.3.3. *On the level of the population*

The decrease in rates of survival, growth and reproduction, as well as the modification of individual behavior – as far as it is due to them – leads to a modification in the population's dynamic, which can go as far as the disappearance of the species in a polluted habitat [CAS 01]. For a single disruption at an individual level, the effect on the population is lesser or greater according to the pattern of the species' life history [SPR 05].

In practice, the pattern of the species' life history is a group of data that includes: the species' biodemographic parameters in a given environment (lifespan, number of developmental stages, number of offspring, fecundity, etc.) and the ratios between these parameters (ratio between lifespan and age at which an organism first reproduces, ratio between rates of growth and fecundity, etc.). Each pattern of the species' life history corresponds to a coadaptation of the species' biological and ecological characteristics depending on the biotic and abiotic factors of its habitat. These characteristics can be classified into two categories. Those that are linked to the developmental cycle of the organism influence the probability of survival above all. Those that are linked to reproduction influence fecundity above all.

Thus, the number of developmental stages and the population’s vulnerability in terms of the probability of survival at these stages are major determinants of a population’s resistance to disruptions [SPR 05]. In effect, among certain organisms, there are critical periods or stages of development during which the organism’s probability of survival is weaker than at other stages [KOE 91]. These stages are particularly vulnerable to instances of pollution. For example, this is the case during periods of larval molts among crustaceans [KOI 92] or the metamorphosis between the larval and juvenile stages of fish (for example, flat fish, which pass from a pelagic larval life stage to a benthic stage during their juvenile and adult phases).

The characteristics influencing organisms’ reproduction, along with their lifespan, strongly influence a population’s response to contaminants [CAL 97, IND 99]. In effect, the number of descendants produced per year in a population depends, according to [SPR 05]:

– on the age of sexual maturity compared to the lifespan and the number of potential reproductive opportunities;

– on the number of reproductions per year;

– on the organisms’ fecundity (the more energy the parent invests in the egg, the less productive it is, but the higher the chance of survival of the egg, and then the juvenile);

– on the existence of parental care of the eggs and/or the young.

In a non-polluted environment, there is no “good” or “bad” strategy in terms of a population’s persistence [SPR 05]. However, certain strategies are more “efficient” than others in terms of persistence when pollution is added to the normal level of disruption in the environment [KAM 96]. For example, in the case of a short and temporary disruption lasting for the duration of the reproductive season, species