CHAPTER 10

Impact of Contaminants on Pelagic Ecosystems

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Abstract: Most of the primary production of the world's oceans takes place in the water column, thereby fuelling not only marine pelagic food-webs, but also most benthic communities. In addition, nearly all marine organisms depend on the pelagic zone for some part of their life-cycle. Although most contaminants have physico-chemical properties that cause them to associate with organic material particles and eventually be transported to sediments, direct contaminant inputs are predominantly to pelagic ecosystems. Taking both the ecological importance and the contaminant load into account, there is a surprising lack of scientific knowledge concerning the effects of contaminants in pelagic systems. The main reasons are presumably the difficulty in linking exposure with processes at a scale relevant for environmental management, and challenges involved in using pelagic fish and zooplankton species for experimental studies (excluding the 2-3 copepod species used for regulatory toxicity testing). Contaminants have been shown to affect primary producers as well as secondary producers-consumers, but there is very limited knowledge about ecological impacts. Top predators in marine ecosystems (piscivorous fish species, marine mammals, seabirds) will be particularly at risk from persistent organic contaminants since they will biomagnify. Although there is evidence of effects caused by such substances in the past, there is a need for continuous updates including “new” contaminants. Most relevant for lower trophic levels, micro- and mesocosm studies under controlled conditions are critical for increased understanding of processes and putative effects of contaminants in the pelagic zone. Some field-based strategies have been suggested and implemented to varying degrees for environmental management of contaminants in the water column, including risk-based modelling, bioassay-analyses of environmental samples or extracts (e.g., through the use of passive samplers), caging of organisms and, finally, collection and analyses of native organisms.

INTRODUCTION

The pelagic zone of the oceans constitutes the single largest ecosystem of the world and contains the organisms that form the basis for most marine food chains and all fisheries resources. The characteristics of the marine pelagic ecosystem have been extensively reviewed [1]. Verity *et al.* [1] clearly indicate that the various forms of anthropogenic impacts on the seas, may result in, *i.e.* overexploitation, habitat changes, extinctions, increased disease, species replacements, and how an integrated understanding of resource availability and predation pressure is required for effective environmental management. As will become apparent later in this chapter, increased concentrations of contaminants may affect both bottom-up and top-down processes. Although causing less obvious effects than, for example, overfishing or habitat modification, contaminants are nevertheless important for our understanding and proper management of human interactions with marine pelagic ecosystems.

There are of course spatial and temporal variation of physical and chemical parameters in the pelagic zone, both vertically and horizontally, but it is comparatively stable compared to habitats in most terrestrial or freshwater ecosystems (e.g., Kaiser *et al.* [2]). However, in terms of productivity there are large differences between areas. Whereas coastal areas and shallow seas are among the most productive per area of any ecosystem on the planet, oceanic areas generally have low biomass and productivity [2]. Sunlight-driven primary production needs to take place in the upper reaches of the oceans, sometimes limited to the upper ten or twenty meters. The part of the pelagic zone with the highest primary production will in most cases also be the area that receives contaminant inputs and will have the highest concentrations of such substances. Although there is an extensive literature on oceanographic trace metals, including non-essential metals such as mercury, cadmium and lead, and their behaviour in relation to hydrographic processes and nutrients [3], there is limited data for organic contaminants (see [4]). Organic contaminants are generally thought to be associated with dissolved or particulate organic material, to some extent inorganic particles, and will thus be gradually removed from the water column through sedimentation. Contaminant exposure to pelagic organisms will therefore be from low concentrations in water, through ingestion of particles with

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somewhat higher concentrations, through uptake of organic material with associated contaminants or through trophic transfer (which would lead all the way from bacteria and protists to marine mammals, seabirds and humans). Although it should theoretically be simple to quantify the relative distribution and bioavailability of a given substance in pelagic waters by knowledge of its lipid-solubility (and hence affinity for organic material), complex biotic and abiotic processes results in concentrations of contaminants in water, particles or organisms that are difficult to predict (e.g., Ruus *et al.* [5], Vethaak *et al.* [6]). The available data support some general observations; for example, bioaccumulation and possible biomagnification of polycyclic aromatic hydrocarbons in invertebrate food chains, but not in vertebrates [7, 8, 9] (but see Berrojalbiz *et al.* [10]), trophic transfer of persistent organic contaminants [11, 12, 13, 14] and mercury [15, 16], and finally, more or less species- and exposure-dependent accumulation of other trace metals [17, 18].

Major sources of contaminant inputs to the pelagic zone are atmospheric deposition, riverine inputs, shipping activities, land run-off and point discharges. A small proportion of marine contaminants will be directly deposited on the seafloor through activities such as dredging or drilling operations. Sediment-associated contaminants may eventually be a source of input to the pelagic zone through diffusion, resuspension or trophic transfer, but there is limited knowledge about links between contaminants in benthic or demersal species and their predators in the pelagic zone. An emerging problem is the presence of plastic debris and associated contaminants. Contaminants can interact with both floating microplastics and plankton, and thus potentially enter food chains that may ultimately affect humans [19]. Preliminary data show that chemicals in plastic microparticles (<1 mm) are being taken up by marine organisms, including mussels [20]. There is as yet limited knowledge of any effects.

A distinction needs to be made between coastal and oceanic areas. Coastal areas are for natural reasons the waters of the world's oceans with the highest inputs and levels of contaminants, but at the same time areas with a high variability in environmental factors such as particle load, primary production, salinity and temperature. About 30% of oceanic primary production occurs in shelf and coastal environments, constituting less than 10% of the total area of the ocean [21]. The factors discussed above will affect the behaviour of contaminants and how they may impact marine ecosystems [22]. Oceanic areas are less variable than coastal areas and sources of contaminants are limited to atmospheric deposition, offshore oil and gas activities, shipping discharges and, to a lesser extent, the presence of plastic debris.

Over the last decade there has been an increasing number of studies reporting the concentrations of contaminants in surface and microlayer water [23, 24], associated with plastic resin pellets [25], passive samplers [26, 27], particulate material [24, 28] and caged or pelagic organisms [5, 24, 29]. As will be discussed in greater detail below, there are obvious problems in trying to assess the effective concentration of contaminants in water-masses, both due to the variable solubility, speciation, association with particles and bioavailability of contaminants and because water-masses move and mix.

There is even less data for contaminant-related effects in pelagic ecosystems. Nearly all marine model organisms for laboratory- or field-based studies on contaminant effects are benthic species, including blue mussel (Mytilus edulis; [30, 31]), dab (Limanda limanda; [32, 33]), eelpout (Zoarces viviparus; [34]) and flounder (Platichthys flesus; [35, 36], [37]). There are however, some studies that have targeted pelagic species or used caged species. The BECPELAG (Biological Effects of Contaminants in Marine Pelagic Ecosystems; [23]) workshop investigated effects and levels of contaminants in pelagic systems through field-collected organisms [38], caged organisms [39] and bioassays of water and passive sampler extracts [40]. Organisms studied ranged from invertebrates to fish. The results from the workshop clearly showed that levels and effects of contaminants in field-collected organisms were less clear than in organisms caged in the same area. Other studies have focused on species at the top of food chains such as swordfish, for which there are indications of relationships between contaminant levels and sublethal endocrine disrupting effects [41].

The aims of this chapter are to review the current understanding of how contaminants affect pelagic ecosystems, outline approaches and to suggest research directions.

CHALLENGES

There are reasons why benthic organisms and systems have been preferred to pelagic systems in contaminant research. As hinted to above, ecological importance is certainly not the reason and many pelagic fish species are as economically important as benthic species. One reason for the preference of benthic species for research in general is accessibility – intertidal or shoreline species require less infrastructure for their collection and study than organisms in the water column. Secondly, benthic species are generally more amenable to being kept in the laboratory and there is hence much more general knowledge about their biology. Thirdly, and possibly most important, concentrations of contaminants are orders of magnitude higher in sediment than in the water column, at least in theory resulting in higher exposure levels for sediment-dwelling than for pelagic organisms. However, exposure levels in the two habitats will vary considerably for different groups of contaminants. Pelagic organisms will generally be exposed to higher levels of the more easily degradable substances than their benthic counterparts. Finally, there is a difference between benthic and pelagic organisms in our knowledge of their exposure history (or at least perceived knowledge). Whereas many benthic species, for example blue mussel, are sedentary and stationary, pelagic species move continuously. Although contaminants may enter marine ecosystems through pelagic waters, there is a feeling that it is easier to quantify exposure for benthic than for pelagic species. In enclosed water bodies such as fjords or estuaries this may be true, but in the open sea it is not obviously a clearer relationship between contaminants in abiotic matrices such as sediment and epibenthic organisms than between concentrations in water and pelagic organisms. Even for benthic organisms there are not obvious quantitative relationships between contaminants in sediment and the tissues of sediment-dwelling organisms [42, 43], and sediment-related factors such as black carbon strongly affects bioavailability even of organic contaminants [8, 44].

One major challenge for understanding contaminant exposure and effects for pelagic organisms concerns their presence in and exposure to different water masses. For planktonic organisms this is not necessarily the case as they will remain associated with a water mass for periods of time, but nekton such as fish will clearly be exposed to different levels of contaminants as they move through more or less contaminated water masses.

A relevant question here is how contaminant exposure in marine ecosystems can be most precisely estimated. For species with low metabolising capacity, accumulated concentrations of many organic contaminants and non-essential metals will be a reasonable estimate for long-term exposure. Other species, and particularly vertebrates, will to a larger extent regulate their intake and accumulation of non-essential metals and metabolise and excrete a variable fraction of absorbed organic contaminants. Although some organic contaminants have half-lives in the range of years in most organisms [45, 46], most are metabolised at least to some extent and some, such as alkylphenols and polycyclic aromatic hydrocarbons, to the extent that tissue residue analyses are less useful than analyses of metabolites in bile or other excretory fluids [47, 48, 49]. As mentioned above, there is a complex relationship between contaminant concentrations in abiotic matrices (sediment, water) and concentrations in tissues, particularly for mobile species. Contaminant exposure may therefore be most accurately determined from tissue concentrations for persistent substances and metabolite levels for others. There are however some other alternatives and we will focus particularly on the pelagic organisms here. There is limited knowledge about the ecotoxicology of this group of organisms, but zooplankton does not appear to metabolise organic substances efficiently [50] (but see Magnusson *et al.* [51]), and they accumulate a range of metals [52] as well organic contaminants [11, 53] and would therefore be a useful matrix by which to estimate exposure in any given water-mass. Using zooplankton for this purpose would however need to be part of a carefully designed experiment to ensure spatial representivity, and vertical migration patterns would need to be taken into account. In the photic zone phytoplankton could be used for the same purpose, although any vertical movement would have to be considered for the species used. A second alternative is to use passive samplers: a range of different materials have been used, including membranes with a lipid inside [54], silicone sheets [26, 55], various plastics [56], coated membranes [57] or polyurethane foam [58]. Common to most passive samplers as they have been deployed until now is the need for a mooring system. Passive samplers are generally deployed for a period of three to six weeks prior to extraction and chemical analyses.

PRIMARY PRODUCERS

Phytoplankton forms the basis of marine food webs and embodies the carrying capacity of marine ecosystems. In the classical view, the main route for organic carbon was through zooplankton feeding on phytoplankton, but it is now well established that microzooplankton, bacteria and probably viruses play crucial roles in affecting the trophic dynamics and composition of plankton communities [59, 60]. Our knowledge of how and whether contaminants affect these organisms and interactions between them is limited.

The increase in primary production in coastal waters since the 1970s, at least to some extent due to increased nutrient inputs, has received much attention from the scientific community as well as from environmental managers. In many coastal systems, phytoplankton blooms are common events and a significant amount of this phytoplankton biomass will sediment through the water column, settle on the bottom and the nutrients be remineralised in surface sediments [61]. Increases in the occurrence of algal blooms have been linked to phenomena such as oxygen deficiency and mass kills of benthic fauna and fish as well as the formation of foam on beaches (produced by algae species such as Phaeocystis) and toxic shellfish.

To what extent will chemical stressors affect primary producers? Given the large amount of new, industrially produced substances, this is an important and relevant issue for the coming decades. Results from experimental studies indicate that certain chemicals may have a direct impact on plankton communities and food chains, and may thus potentially affect the carrying capacity of estuarine and coastal ecosystems. The most important compounds for causing toxic effects upon phytoplankton are pesticides and biocides, especially those with a herbicidal mode of action. The antifouling agent TBT has been shown to affect phytoplankton communities at concentrations that are present in coastal waters [62]. Effects include reductions in population development rate and shifts in species composition – *i.e.*, towards species that are more tolerant to TBT pollution. Worldwide measures to restrict TBT in antifouling paints (with a total ban by 2008) has lead to the development of alternative antifouling compounds such as zinc pyrithione (ZPT), copper pyrithione (CPT), Irgarol 1051 and diuron [63, 64, 65]. Residues of these novel antifouling agents are currently found worldwide, especially in estuarine and coastal waters near and in contaminated marinas. Irgarol 1051, like other triazine herbicides, is a strong inhibitor of photosystem II and reduces growth and productivity of sensitive phytoplankton species [66]. Some phytoplankton species appear to be more sensitive to Irgarol 1051 than others. For example, a 23-h exposure to Irgarol (112 ng/L) decreased the abundance of some eukaryotic species to less than half of the controls [67]. Zamora-Ley *et al.* [63] found in a marine harbour that Irgarol 1051 caused changes in several phytoplankton species with increasing herbicide concentrations.

Maraldo and Dahllöf [64] found that the acute toxicity of the antifouling agents ZPT and CPT among natural phytoplankton communities was similar to that of TBT [62], which in turn was higher than those reported for Zn and Cu alone [64]. The sensitivity towards ZPT and CPT was dependent on the phytoplankton community structure and the density of algae and suggested an enhanced effect of ZPT and CPT under phosphate-limiting conditions.

The effects of the herbicide atrazine on marine phytoplankton typical of the German Bight (North Sea) were demonstrated in mesocosm experiments [68]. The authors reported reduced photosynthesis accompanied by lower chlorophyll concentrations and reduced primary production. Other recent experimental work have demonstrated that the pharmaceutical clotrimazole can affect marine microalgal communities at picomolar concentrations, but the true potential for impact on marine primary producers has not been established [69].

The development of plankton communities in estuarine and coastal waters is governed by highly dynamic physical and chemical processes. This makes it hard to predict or establish the effect and ecological significance of chemical compounds on these communities. The potential impact of chemicals on phytoplankton and phytobenthos communities in coastal waters is known to depend on environmental factors such as salinity, temperature, nutrients, and exposure to UV-A and UV-B radiation and contaminants. Although contaminants may affect phytoplankton, any effects might be masked by other factors and interactions. To tackle this problem field studies complemented with mesocosm experiments should be conducted to improve control over factors and to improve the ecological relevance of the findings.

Another aspect of chemical stress on plankton and other organisms higher in the food chain are natural toxins produced by marine algae. As a consequence of changes in the coastal zone, the frequency and intensity of toxic algal blooms might increase, resulting in increased levels of natural toxins. The risk of toxic algal blooms can also increase as a result of unintended introductions of new invasive species, for example by ballast water releases. However, it remains difficult to quantify ecological impacts of such natural toxins because available toxicity data are limited. The relative contribution of anthropogenic chemical compounds and natural toxins on the total chemical pressure under field conditions is therefore unknown, and we lack insight into any interactions between these groups of chemicals.

SECONDARY PRODUCERS AND TERTIARY CONSUMERS

Secondary production includes the consumption of primary producers and biomass generated by heterotrophs. Tertiary consumers include predatory fish and fish-eating mammals and birds. Long-term changes of offshore zooplankton appear to be mainly associated with climatic and hydrographic phenomena [70]. Any direct or indirect effects of contaminants on marine zooplankton are not well understood. Bioaccumulation of metals and organic contaminants in marine zooplankton including jellyfish has been reported, [71, 72]. An obvious challenge in this context is the identification and separation of different species in a sample. In a comprehensive study, Hoekstra and co-authors concluded that concentrations of organic contaminants in zooplankton predominantly reflected chemical partitioning and that there was limited biotransformation by the *Calanus* species investigated [71]. Although organochlorine contaminants do not appear to be metabolised extensively by zooplankton, there is some evidence that polycyclic aromatic hydrocarbons may be [10].

Toxicity information for zooplankton is limited, except for the few species used in toxicity testing (mainly *Acartia, Nitocra*, *Tisbe* and mysids, [73, 74, 75]), although there is some indication that, e.g. insecticides affect coastal zooplankton [76]. Toxic effects have been shown for TBT at concentrations present in coastal waters [77]. The observed effects included reduced population development rate and shifts in species composition.

A high potential for bioaccumulation of endocrine disrupting compounds (*i.e.*, organotins, flame retardants) and indications of endocrine disrupting effects have been demonstrated for the estuarine mysid *Neomysis integer* [72, 78]. This species plays a key role in the transfer of energy between phytoplankton and fish production in estuaries and along shallow coastal waters in northern Europe, and between benthic and pelagic food webs. Furthermore, some studies have investigated effects of contaminants on population-level effects in the ecologically very important copepod genus *Calanus* [79, 80]. A limited number of studies have evaluated the application of sublethal effect protocols and biomarkers, in phyto- and/or zooplankton species [78, 81]. However, there have been some recent studies using transcriptomic approaches for ecologically important *Calanus* species [82, 83, 84].

A number of studies indicate that eggs and larvae of pelagic and demersal fish that float in surface and subsurface layers may be particularly sensitive to diffuse contaminant exposure (including PAHs from oil pollution) and sublethal effects [85, 86, 87]. Unfortunately, the full impact of contaminants on critical life stages of fish and other nekton is still largely unknown.

Several studies have demonstrated effects of contaminants on sublethal responses in selected pelagic fish species. In studies with saithe (*Pollachius virens*) as part of the BECPELAG workshop, tissue-level effects were observed in fish collected close to a production platform in the North Sea [88]. A North Sea monitoring study using a predominantly demersal feeding species, haddock (*Melanogrammus aeglefinus*), reported a range of effects in this species linked to the presence of populations in or near areas with offshore activity [89]. There were substantially increased levels of DNA damage and changes in the lipid composition of membranes in haddock collected in areas with high offshore activity. The effects were corroborated by other biomarkers and showed a total picture of a population with increased DNA damage mainly due to PAH exposure (indicated through elevated PAH metabolite concentrations), but also increased oxidative stress resulting in changed lipid composition [89]). However, the ecological significance of the observed effects remains unresolved.

Fossi and co-workers [41] showed that large pelagic predators, bluefin tuna (*Thunnus thynnus*), swordfish (*Xiphias gladius*) and Mediterranean spearfish (*Tetrapturus belone*), contained increased levels of vitellogenin (VTG), a yolk precursor protein only expected to be present at appreciable quantities in female fish. Such levels are most likely caused by accumulation of endocrine-disrupting substances through their diet. Another study by De Metrio *et al.* [90] supported these findings and showed that close to a quarter of caught male Mediterranean swordfish (*Xiphias gladius*) displayed ovotestis (intersexuality), again possibly caused by endocrine-disrupting compounds (EDCs). Furthermore, elevated VTG levels were found in liver tissue. The causes of these phenomena are not yet known, but bioaccumulation of endocrinologically active substances is a possible explanation. The evidence of wide-spread EDC exposure in the marine environment is supported by studies of Scott and co-workers [91, 92], who observed offshore male cod (*Gadus morhua*) and male dab (*Limanda limanda*) with elevated levels of VTG.

Because of bioaccumulation and biomagnification processes in food webs, globally distributed persistent organic pollutants (POPs), including EDCs, may attain high concentrations, in pelagic top predators. Such substances may reach levels that result in effects on reproductive and/or immune systems. This has been well illustrated in field studies on Baltic grey and ringed seals, and semi-field studies with Wadden Sea harbour seals. Those studies have shown that reproduction and immune functions can be impaired in top predators following biomagnification of PCBs in the food chain (see review by Vos *et al.* [93]). Reproduction effects have resulted in population declines and may also have contributed to the mass mortalities observed in some European seal populations due to virus infections.

Numerous other cases refer to mass mortalities by infectious diseases, poor reproductive performance, immunosuppression, thyroid abnormalities and other non-reproductive disorders in marine mammals and fish-eating birds (for reviews, see Vos *et al.* [93] and Law *et al.* [94]). Such effects have to some extent been associated with the presence of POPs (e.g., organochlorine compounds, brominated flame retardants and metabolites) and other endocrine disrupting and/or immunotoxic compounds in the body fat [95]. Bennett *et al.* [96] found an association between chronic exposure to mercury and infectious disease in harbour porpoises. An increase in disease susceptibility in contaminant-exposed whale and dolphin populations has further fed speculation about a possible negative influence of contaminants on the immune system [97]. Accumulation of persistent and lipophilic contaminants, including polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and coplanar polychlorinated biphenyls (coplanar PCBs), were found in several albatross species feeding in the open oceans, specially the North Pacific Ocean. Possible adverse effects of these compounds to these birds may be expected from toxic equivalent (TEQ) levels [98]. However, in most of these cases, it was not possible to confirm a cause-effect relationship between a specific chemical or group of chemicals and individual or population level effects. Studies over the last decade have shown high concentrations of a range of substances of concern in marine top predators, including TBT [99, 100], toxaphenes [101], polybrominated diphenyl ethers [101, 102, 103, 104], perfluorooctane sulfonates PFOS and perfluorooctanoic acid PFOA [105, 106]), nonyl- and octylphenol [107] and phthalate esters [108]. Single and combined impacts of food-chain accumulation of these contaminants and subsequent high concentrations in marine pelagic secondary producers and tertiary consumers has yet to be elucidated. In addition to the above, increasing levels of human pharmaceuticals, personal care products and aquaculture veterinary pharmaceuticals in coastal pelagic ecosystems is an area of concern with limited knowledge of any ecological impacts [109].

INTERACTIONS BETWEEN ENVIRONMENTAL FACTORS

Three of the most obvious pressures from human activity in marine waters are eutrophication, oil and contaminant inputs. For eutrophication there is extensive data on nutrient and bloom dynamics in coastal areas [110]. There are large amounts of data on the environmental physiology of many algal species. There is also a substantial body of knowledge on how oil and offshore-related discharges affect marine ecosystems, not least from monitoring following accidental spills from, for example, Exxon Valdez [111] or Prestige [112]. Aspects of the consequences of offshore-related effluents were evaluated recently through the BECPELAG workshop [23]. Finally, there is a large literature on the presence and effects of contaminants in coastal ecosystems even at low exposure levels [113]. Although there is limited evidence of large-scale effects of contaminants in marine ecosystems, possibly with the exception of Puget Sound, USA [114] and the North Sea and Baltic in the 1970-80s [86, 115], there is reason to believe that chronic exposure to low levels of contaminants will affect pelagic organisms.

Eutrophication, oil and contaminant inputs are co-occurring features of most estuaries and harbours in industrialised countries. Organic enrichment, the presence of oil, contaminants and variable oxygen availability would be expected to interact in their effects on marine biota, but there are surprisingly few studies on whether and to what extent this is the case (but see Gunnarsson *et al.* [22] and Herman *et al.* [116]). Natural waters contain both dissolved (DOM) and particulate organic material (POM), both of which may act as “sponges” to mop up organic and many inorganic contaminants in the water column. Increased levels of organic material could therefore be expected to modulate effects of contaminants through decreased bioavailability in water or increased sedimentation and “co-precipitation” of contaminants. For filter-feeding organisms in the water column, association of contaminants with particles may actually increase exposure as both food and water will contain contaminants. For predators this process would decrease water-borne exposure, but increase exposure through the food chain. Water-soluble components of oil would behave as other contaminants in this context, whereas dispersed oil would be expected to behave like DOM. It is not clear how algal, bacterial and protist interactions may be affected, although specific effects from contaminants on any one group would be expected to affect energy and nutrient flows in the network. Association of contaminants with particles will generally decrease residence time in the water column and thus shift exposure from pelagic to sediment ecosystems.

Despite existing knowledge about eutrophication effects in pelagic systems, there is a need for further knowledge about how natural systems behave under conditions of varying nutrient or carbon availability and there is limited understanding about how oil or contaminants may interact in such systems. Small-sized organisms could be thought to be at greater risk since they would be expected to accumulate higher concentrations of contaminants, but organisms that accumulate non-limiting substrates may also have a high uptake [117]. The question remains whether organisms that accumulate high concentrations of contaminants are most sensitive to the effects of the contaminants. In addition to ecological consequences of modulating the systems themselves, changes in both small and medium scale pelagic processes could strongly affect fluxes and effects of contaminants in coastal ecosystems through affecting sedimentation and transfer to higher trophic levels.

Combined effects between UV radiation and contaminants on plankton community structure in coastal zones have been observed in several recent studies. Major coastal and marine contaminants that still often exceed environmental risk limits in estuarine and coastal waters, such as TBT, PAH, Irgarol or atrazine have phototoxic capacity and proven or suspected impact on planktonic species composition and communities. Microphytobenthos and phytoplankton might be especially sensitive to such phototoxic effects. What appeared to be a synergistic interaction between TBT exposure and UV-B radiation effects on a natural planktonic assemblage was found by Sargian [118] and Pelletier *et al.* [119] using a microcosm approach. Deleterious effects of TBT exposure were significantly more pronounced when cells were co-exposed to enhanced UVB levels. The same author also found a reduced bacterial production in the presence of TBT. Hjorth and co-workers [120] observed effects of the polycyclic aromatic hydrocarbon pyrene on a natural marine plankton community using a food-web approach in a mesocosm. Direct and indirect effects on the function and structure of bacteria, phytoplankton and to a lesser degree on zooplankton communities were found. The change in system function suggested that PAHs might be an important stress factor for pelagic systems, as a one-time exposure of a single compound changes the development of a pelagic community.

An important finding was recently reported by Echeveste *et al.* [121]. These authors performed *in situ* experiments on board of a research vessel in the NE Atlantic Ocean that determined the influence of complex mixtures of organic pollutants on oceanic phytoplankton populations. The results of these experiments suggest that current levels of POPs are only 20 times below the levels at which significant influence on ecosystem function (primary productivity) would be found.

Table 1: Alternative strategies for pelagic environmental assessment.

Approach	Advantages	Disadvantages	References
Exposure and/or effect modelling	Reproducible; Direct link to risk assessment.	No direct link to environmental impact.	[27, 122]
In situ extracts	Identify specific mechanisms and substances; Sensitive and reproducible; Possible to test systems not otherwise included (e.g., early life stages in fish).	Limited volume/area; Laboratory testing for effects.	[40, 123 - 125]
Caging	Reflects local exposure over deployment period; Can use organisms with desirable characteristics.	"Semi-natural" exposure situation; Food availability unknown; Exposure at one point.	[26, 29, 39, 126]
Mesocosm studies	Can control vital parameters. Some ecological relevance; Improves scope for interpretation.	Reduced biological and physical complexity relative to field situation.	[6, 68, 77, 118, 120]
Field sampling	High ecological relevance.	Difficult to assess area integrated over; High natural variability.	[38, 89]

APPROACHES

There are substantial logistical challenges involved in the study of how contaminants may affect pelagic systems or species. Micro- or mesocosm studies are required for detailed studies of specific effects or interactions between factors. For lower trophic levels, mesocosm studies are generally required to assume any kind of ecological relevance. In the field, four approaches have been used:

I. modelling of contaminant distribution and subsequent effects by comparing with lab-data;
II. estimating exposure through whole-water extraction or passive samplers and either model effect – as for (i) – or measure using a battery of bioassays, e.g., *in vitro* techniques;
III. cage organisms in the area of interest;
IV. mesocosm studies; and
V. field-collection of organisms.

The five approaches all have weak and strong characteristics, outlined in Table **1**.

RESEARCH NEEDS

As will be apparent from the above, there are large blank areas in our understanding of how and whether contaminants impact pelagic ecosystems. On the other hand, knowledge of the pelagic zone is clearly vital in the management of our oceans. In this context it is important not to view the pelagic zone in isolation, but remember that pelagic processes are important to both the surface layer and benthic ecosystems. Future research should be directed towards integrating and not dividing our understanding of different environmental compartments.

As for all other fields in ecotoxicology, we face a major challenge in developing methods to assess the effects of contaminant mixtures. For pelagic systems this may be particularly relevant since even the less persistent contaminants will be present in the water column near the source. In addition to contaminant mixtures, there is a scarcity of knowledge on how other factors modulate contaminant impacts or combination effects. Micro- and mesocosm model systems (see below) should be useful tools in this context.

It will be clear that there is a need for an improved understanding of how contaminants affect both primary producers and microbial loop components. Current knowledge is limited to effects on single algal species and there is virtually no knowledge of impacts in more complex systems that include bacteria and protists.

There is some understanding of how some contaminants affect a limited number of zooplankton species (e.g., calanoid copepods), but little is known about the wide range of mesozooplankton species, including metamorphosing stages and effects on their sensory systems [127].

It is inherently challenging to keep pelagic fish species and their early life stages for experimental studies due to the need for specialised sampling techniques and large volume aquarium systems. In contrast to primary producers and zooplankton, there is a substantial knowledge of general physiology and biochemistry that can be applied for fish, even though there may be species-dependent contaminant-associated effects. There are even larger obstacles involved in experimental studies of pelagic top predators.

In addition to experimental micro- or mesocosms, four approaches have been used for the assessment of contaminant effects in marine pelagic ecosystems: modelling, *in situ* extracts/passive samplers, caging and field collection. Both laboratory- and field-based methodologies are needed and they complement each other.

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