Biological pollutants and biological pollution—an increasing cause for concern

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Abstract

There are increasing concerns regarding the delivery, movement and presence of non-indigenous or invasive species into marine and estuarine areas. Such introductions can be on a large scale such as the movement to higher latitudes of species as the result of global warming. Alternatively, such species can be introduced into a marine or estuarine area as the result of small-scale events, such as the liberation from waste-water discharges, aquaculture or ballast-water discharge. However, if such introductions lead to a successful colonisation then they can become a wide-scale problem. This paper considers the introduction of such non-indigenous and invasive species as biological pollution and biological pollutants and it discusses the definitions and concepts used in assessing and managing marine pollution in relation to these terms.

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1. Introduction

There is an increasing set of case studies regarding the presence and movement of invasive species in marine and estuarine waters (see references appended here as examples) and the term biological invasions has become widely accepted. Such species are also termed exotics and non-native invaders. However, recently the terms biological pollutants and biological pollution have been used to discuss the problems caused by such invasive species (e.g. Boudouresque and Verlaque, 2002). Despite this there appears to be some confusion regarding the terms biological pollution—it can be taken to mean pollution emanating from organisms, such as nutrients or organic matter, and even pollution affecting biological organisms. This paper aims to discuss these concepts and definitions.

The studies and assessment of marine pollution are underpinned by a set of definitions (Table 1, columns 1 and 2), most of which have a basis in relation to chemical inputs. This article considers the increasing problem of biological pollution by assessing those definitions in relation to biological organisms as agents of pollution, i.e. as contaminants and/or biological pollutants as agents of change in the marine environment. As indicated in the definitions, we are fully acquainted with the chemical-pollution based language and philosophies but the debate here is whether there is now the need for the definitions to be changed or amended in order for them to be applied to organism-based pollution. Such an approach can also be developed to consider physical pollutants in the scope of the definitions, i.e. to include as pollutants large-scale physical structures (such as bridges, harbours) as well as small-scale physical materials (such as soil from erosion, colliery waste); however, that is for discussion elsewhere.

2. Types of biological pollutants

The central criterion of the definitions of pollutants is their ability to reduce the fitness for survival of some level of biological organisation (from cell to ecosystem). If it is agreed that the term ‘biological pollutant’ is valid then it will be necessary to determine whether such a reduction in fitness can be demonstrated and then to
### Table 1
Definitions of terms used in chemical pollution and their translation for biological pollution

<table>
<thead>
<tr>
<th>Term</th>
<th>Chemical-based definition</th>
<th>Translation, with examples, to biological pollution</th>
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<tbody>
<tr>
<td>Pollutant</td>
<td>A substance introduced into the natural environment as a result of man’s activities and in quantities sufficient to produce undesirable effects.</td>
<td>The input and effects of micro- and macro-organisms on the condition that adverse effects can be demonstrated.</td>
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<tr>
<td>Pollution</td>
<td>(i) is a change in the natural system as a result of man’s activities; (ii) has occurred if it reduces the individual’s/species/community’s fitness to survive; the introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as to harm living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of seawater, and reduction of amenities (GESAMP).</td>
<td>The effects of introduced, invasive species sufficient to disturb an individual (internal biological pollution by parasites or pathogens), a population (by genetic change) or a community (by increasing or decreasing the species complement); including the production of adverse economic consequences.</td>
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<tr>
<td>Contamination</td>
<td>An increase in the level of a compound/element (“pollutant”) (as the result of man’s activities) in an organism or system which not necessarily results in a change to the functioning of that system or organism.</td>
<td>The introduction of species without noticeable effects (e.g. microbes which are killed immediately by natural conditions, possibly to be extended to species occupying available and vacant niches).</td>
</tr>
<tr>
<td>Responses to pollution</td>
<td>(i) lethal-organisms are killed thus resulting in community change; (ii) sub-lethal effects which may occur before the concentration of toxic substances reaches lethal levels; used as an early warning of pollution.</td>
<td>As seen by a reduction in health due to pathogens and parasites and the loss of genetic fitness due to escapees; the alteration in community structure with single invasive species at low densities may be difficult to detect.</td>
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<tr>
<td>Stress</td>
<td>The cumulative quantifiable result of adverse environmental conditions or factors as an alteration in the state of an individual (or population or community) which renders it less fit for survival.</td>
<td>Discharges of organisms via ballast water may be regarded as episodic although there may be an insufficient inoculum to establish a population.</td>
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<tr>
<td>Episodic pollution</td>
<td>Major but often short-lived (temporary) discharges, e.g. shipping accidents.</td>
<td>Regular, continuous inputs of organisms as escapees from widespread aquaculture or the dispersive, reproductively viable stages of non-native cultured organisms which have adapted successfully and become reproductively viable; the gradual movement of species through widespread temperature change.</td>
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<tr>
<td>Chronic pollution</td>
<td>Diffuse, low-level inputs which cannot be traced to a particular incident, e.g. rivers, atmosphere; may contribute 90% of total inputs; often the cause of effects which are sub-lethal and difficult to detect.</td>
<td>It is difficult to use this term for most biological pollutants; its possible use is for pathogenic micro-organisms discharged from waste-water outfalls.</td>
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<tr>
<td>Acute pollution</td>
<td>Concentrated pollution, with an identifiable source and readily observed effects; often the cause of lethal effects.</td>
<td>An extension of this term is required to indicate the aesthetic aspects of changes to natural faunal and floral communities, i.e. a reduction in ‘naturalness’.</td>
</tr>
<tr>
<td>‘Aesthetic pollution’ (sic)</td>
<td>Unpleasant material likely to cause visual or olfactory offence but which (usually) causes little biological harm.</td>
<td>The uptake and accumulation (culture) of pathogens in filter-feeding bivalves may occur although there also may be the production of resting stages; the accumulation after successful reproduction of invasive species in a community.</td>
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<tr>
<td>Bioaccumulation</td>
<td>An increase with time in the content (or body burden) and/or concentration of a contaminant within an organism.</td>
<td>It is difficult to argue for this in relation to biological pollution although the successful establishment (and displacement of indigenous species) of an invasive population could be regarded as biomagnification.</td>
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<tr>
<td>Biomagnification</td>
<td>The occurrence of increasing levels of a pollutant with a movement from the lower trophic strata to the higher trophic strata.</td>
<td>The release of pathogens from waste-water discharges, of genetically modified organisms from aquaculture or parasites from transplanted shellfish.</td>
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<td>Direct input</td>
<td>A point source discharge, often the cause of acute pollution.</td>
<td>The changes in distribution and thus movement to higher latitudes of species through man-induced global climate change.</td>
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<tr>
<td>Indirect (or diffuse) input</td>
<td>A widespread, low-level discharge often likely to result in chronic pollution.</td>
<td></td>
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consider whether this applies across such a wide range of organisms which may be regarded as pollutants. It is relatively straightforward to include viruses, bacteriophage and bacteria; these are liberated from waste-water discharges into the sea ostensibly to kill them but they can accumulate in sediments and in filter-feeders thus, presumably, changing the microbial floral community in those media. However, it is questioned whether we should also include protozoans and other invertebrates—barnacles such as _Elminius modestus_ introduced into European waters; other crustaceans such as the Chinese mitten crab _Eriocheir sinensis_, molluscs such as _Crepidula fornicata_, _Mya arenaria_, and _Mercenaria mercenaria_; polychaetes such as _Marenzelleria viridis_. Several of these species were introduced decades ago, probably from the discharge of ballast water, such that they are now assimilated into the NW European marine fauna. However, there is the need for further studies to determine how the recipient communities have been changed as the result of the introductions or whether they have been assimilated without effect.

The role of macrophytes as harmful invasive species, i.e. biological pollutants, appears to be more clear. For example, plants such as the green alga _Caulerpa taxifolia_ are well known as an invasive species to the Mediterranean, an example of a ‘successful’ biological pollutant—Boudouresque and Verlaque (2002) indicate that of 85 species as biological introductions, only about nine can be regarded as invasive. With regard to higher organisms, there are good examples for the immigration of fish species to higher latitudes (e.g. Stebbing et al., 2002), a feature correlated with increased temperatures. However, and using a particular example, although fishes such as the Lionfish _Pterois volitans_ are accepted as invaders, probably introduced with ballast water or by aquarists (Whitfield et al., 2002), it is questioned whether these should be termed biological pollutants, i.e. whether they have reduced the fitness of the biological system for survival.

In the estuarine and marine field, there are several good examples of introduced species and of the damage (both biological and at the socio-economic level) caused by them. For example, the Chinese mitten crab _E. sinensis_ now extends to a large part of NW Europe from the Tagus Estuary in Portugal to northern Germany and eastern Scotland and it has started causing damage to flood defence walls by burrowing. The damage here is at an ecosystem level as well as affecting local community structure. As another example, introduced and in some cases genetically modified species are released, such as non-native oysters producing spat in South-west Britain and chromosome-modified salmonids escaping (or even being liberated) from fish farms in Scotland and Norway. It is notable that the recent (Summer 2002) flooding in central Europe has inadvertently caused the release of hybrid and modified fishes, such as sturgeon (_Acipenser_ spp.) from aquaculture installations (pers. com. Dr Krystof Skora, University of Gdansk Marine Station, Hel). In these cases, if the organisms survive and successfully breed then the biological pollutants can be regarded not only as conservative, i.e. persistent, but also accumulative.

Micro- and macro-parasites and micro-pathogens have long been regarded as introduced and invasive species—these may be either non-natural or natural but in the wrong place. For example, mammalian gut flora liberated into the marine environment can be regarded as the wrong microbes in the wrong place at the wrong time. Hence it is necessary to consider the spatial extent of the liberation and movement of organisms—from the large scale with an underlying change in their distribution to small-scale liberation from sewage pipes and aquaculture. However, in contrast to chemical pollutants, the small-scale liberation of organisms has the potential not only to disperse but also to cause an increase in the ambient population, thus becoming a large-scale problem. Given some of these examples, it appears necessary to make a distinction between invasive species, introduced species and biological pollutants.

3. Modification of underlying philosophies

The essence to determining the effects of pollution is that, because of the inherent variability in the natural system, our aim is to detect a ‘signal’ as a change in some component against a background of ‘noise’ and thus we require the use of techniques which maximize the ‘signal
to noise’ ratio. This is then to be followed by the prediction and quantification of effect (hence scientific questions and approaches) followed by the reduction or removal of any effect (hence socio/economic/political questions and approaches) (e.g. Elliott and Hemingway, 2002).

Despite the differences between chemical and biological pollutants, the philosophy of impact detection remains the same in that we are still attempting to detect a signal to noise ratio. For example, we are required to detect an elevated level of pathogenic micro-organisms over and above the background, inherent variability, or an increase in the diversity of a macro-biological community as the result of an additional invasive species. However, the latter is particularly difficult to detect using community statistics, even multivariate methods, given the large, inherent natural spatial and temporal variability in community composition. Using such a purely quantitative treatment of community data, the detection of a single invasive species amongst a diverse, marine community will be particularly difficult. Because of this, the taxonomic approach to describing community structure will be increasingly required.

There may be specific ways in which we cannot transpose the definitions from chemical pollutants to biological pollutants. For example, the accumulation of biological pollutants can occur within an organism (for micro-organism pathogens) or within a community (for genetically modified escapees or introduced invertebrates) but what of the environment’s ability to receive such pollutants without adverse effects being detected? In considering chemical pollutants, we have long discussed and in many cases used and relied upon the ability of the seas to disperse, degrade and assimilate the materials. We have attempted to measure the assimilative capacity of bodies of water and even based legislation and environmental response on such a capacity. For example, the implementation of the European Union Urban Waste-water Treatment Directive (91/271/EEC) is based on the ability of a body of water to absorb organic and nutrient pollutants without adverse effect (Elliott et al., 1999). Is this where our discussion of biological pollutants has to diverge or can we determine the assimilative capacity of a body of water with respect to new organisms?

With respect to introduced pathogenic micro-organisms, the cold, saline and high UV environment of the coast can disperse and degrade the sewage-derived organisms (hence the basis of using long-sea outfalls within the EU Bathing Beach Directive, (76/160/EEC)). The basic premise of using long-sea sewage outfalls, as in many coastal, developed states, is the sea’s ability to dilute, disperse and kill potentially pathogenic gut micro-organisms. Since the mid-1970s this has often been the preferred method of disposal. However, it is becoming increasingly evident that such micro-organisms can remain in sediments, even if not the seawater, and may be harvested by suspension feeding invertebrates. Furthermore, if it is confirmed that such micro-organisms are concentrated within those feeders, then is this an example of bioaccumulation and biomagnification?

Despite such considerations of micro-organisms, can we determine the ability of a marine community to assimilate without effect any new, introduced or invasive macro-organisms? In doing this, we either have to attempt to determine any spare capacity within a community structure for assimilating such organisms or to take the view that no new niches are available or created and so any invasion has, by definition, to have biological repercussions. The assimilation of another species into a community may be possible without biological impact if there is a vacant niche available for colonisation but in most ecosystems there is not a redundant capacity to assimilate additional species without other, natural species or life stages being displaced. Furthermore, even if we agree to the basic concept, it is probably impossible within such a complex environment as estuarine and coastal areas, to measure that assimilative capacity.

Despite the above, in discussing the topic of biological pollutants, there are many aspects in which introduced biological organisms can be regarded as being no different from chemical pollutants. As with the identification, assessment and control of all anthropogenic activities, it is possible to use the DPSIR approach (Elliott, 2002). The Drivers and Pressures emanating from increasing navigation and ballast-water discharge and from aquaculture will change the Status of and produce Impacts on the biological community (at the micro-, macro- and mega-organism level). In turn, such a change will need a Response at the socio-economic, technological, administrative and legislative levels. The latter may require controls on organism inputs or eradication programmes and such a response has to apply to organisms from the single cell to large invertebrates. For example, there has to be a control on the movement of species from the large scale, through the International Maritime Organisation’s ballast-water controls, to small-scale control. An example of the latter is the control by fisheries managers and sea fisheries committees in England and Wales under powers to prevent the movement and relaying of marine mussels in an effort to control the spread of infestation by the copepod *Mytilicola intestinalis*. This illustrates the fact that just as with any type of pollutant, we have developed ways (albeit that some are not very effective) of trying to limit the transport and introduction of unwanted organisms.

With regard to aquaculture, again using the DPSIR approach, we require the additional fish and shellfish as food (the overall Driver) which leads to specific Pressures (such as the need for fish with high growth rates, or the importing of faster growing (perhaps initially
sterile) shellfish species). The altered Status and thus Impacts due to a changed population, community and ecosystem has then initiated Responses such as the EU Directives on the release of Genetically Modified Organisms (90/219/EEC, 90/220/EEC, 98/81/EEC, 2001/18/EC). However, we must question whether all man-induced introductions of organisms are to be regarded as pollutants, for example the use of wrasse as cleaner fish in aquaculture to avoid the need for using chemical anti-pest treatments.

As with chemical pollution and pollutants, there are changes due to biological pollutants at all levels of biological organisation. There are cellular responses as indicated by an immunological response as shown in fish and crustaceans exposed to sewage discharges, and by NW European common seals affected by the phocine distemper virus. There are changes at the individual (whole organism) level, again demonstrated by the above examples as well as in oyster populations infested with imported parasites, leading to population changes. As a further example, there are population genetic changes and perhaps a loss of genetic fitness through the escape of cultured fishes in aquaculture. Finally there are changes to community structure with the introduction of invertebrates (such as C. fornicata, M. arenaria, E. modestus, Ensis directus introduced to European waters from North America and Australasia). Despite this, can one argue that the community with the new species has a reduced fitness for survival or is it merely a new state which may have the same functioning as previously?

As another form of biological pollution, genetic pollution may be regarded as occurring if the natural genetic structure has changed as the result of invasions but again there is the major difficulty here of determining the ‘natural’ genetic structure and that altered as the result of invasions. Such a change is now being determined both with marine plants and animals. For example, the possible invasion of a non-native genotype of the dominant reed of estuarine wetlands, Phragmites australis, itself an original invader, may have increased the invasive potential of the plant (Saltonstall, 2002).

It is of note that those in Europe charged with implementing the EU Habitats & Species Directive (92/43/EEC) will have to determine changes to the designated species and habitats as the result of introduced species. For example, it is often the case that threatened species, and thus those designated for protection under the Directive, will be fragile and endangered. They may be rare as the result either by being at the limit of their distribution or because there is an unsuitable or threatened habitat (Elliott and Hemingway, 2002). They may have a minor role in the community structure but also, because of their low numbers, may be less well-understood. Hence they may be the species most susceptible to the affects of introduced and invasive species but also, because of the poor knowledge base, they present cases where the effects are most difficult to assess and quantify.

The above examples and considerations indicate that many of the definitions and concepts used in marine pollution assessment and control can be translated with respect to biological pollution and biological pollutants (Table 1, columns 1 and 3). As indicated in the table, there are examples for the use of these terms. However, some of the terms require an alteration in our thinking, for example those for acute pollution and biomagnification, but even these can be related to invasive and introduced organisms.

4. Further research and challenges

It is considered here that the biology of invasions should be a priority for further research and that especially we need the ability to study, even by hindcasting, the effects on communities of species introduced over the past century. We have good information and case studies for marine macrophytes and for invertebrates in freshwaters (such as the zebra mussel, Dreissena polymorpha (Mills and Holeck, 2001)) but we need further to consider the repercussions of introduced marine invertebrates and higher organisms as well as the changes to whole marine ecosystem structure. We need to know the mechanisms by which a biological pollutant can be assimilated into the community, to fulfil any available niche or to displace a less suited species from a niche, perhaps within large, unbounded marine systems. Following this, we need to be clearer in our thinking with regard to ‘harm’ being causes by the invasion.

At the macro-organisms level, in considering biological invasions, we have the difficulty of how to separate ‘natural’ invaders from man-induced ones. Natural migrations of organisms are common, especially when linked to natural climatic cycles, for example warm years inducing (in the northern hemisphere) the northward movement of more southerly species and cold years creating the converse. Similarly, high rainfall will allow brackish species to penetrate further into estuaries whereas low freshwater inputs to estuaries allow an increased marine incursion. But we have the additional problem of determining the extent of anthropogenic effects on large and small scales. For example, on a large scale, of man-induced global warming in which species distributions will change, and small-scale problems of species migrating into warm water areas produced by coastal power-plant cooling water discharge.

At the micro-organism level, in considering invasive species, there is the need for further study to separate those invasive species causing primary damage, such as pathogenic micro-organisms liberated from waste-waters and parasites escaping from introduced organisms.
macro-organisms, from those causing secondary damage. The latter includes micro-organisms entering higher organisms after damage through exposure to chemicals, such as micro-organisms invading ulcers in flatfish created by contact with sediment-bound contaminants (Elliott and Hemingway, 2002).

There is the need to determine not only the biological repercussions of the invasions and of biological pollution but also the socio-economic consequences. The latter may require a rethink of how we determine interspecific competition and its role in bioeconomic models (Barbier, 2001); in particular there is the further need to quantify the economic costs of species’ presence. For example, Boudouresque and Verlaque (2002) consider that invasive species should be defined as playing a conspicuous role in the recipient ecosystems, taking the place of keystone species and/or being economically harmful. This is a useful definition for invasive species but there are possible exceptions. For example, how does this square with, for example, the introduction of the central European fish species *Neogobius* into the Polish Baltic coast in sufficient numbers to be commercially viable (pers. comm. Dr Krystof Skora, University of Gdansk Marine Station, Hel)?

It is considered here that the main difficulty is to determine whether the biological effect, needed to confirm that invasive organisms are to be treated as pollution and not just contamination, has occurred, i.e. has a cell, individual, population, community or ecosystem suffered through the input of the organisms or has it merely accommodated any change; has its fitness for survival decreased? Presumably, the introduction (through human activities) of any species must be regarded as contamination (as presence but no biological effect) but the challenge is to determine whether this is translated through to pollution per se. However, if it is a non-indigenous organism which has been introduced into the community then by definition there is a biological effect, even if only to extend the diversity of the community, although again one questions whether this is regarded as an adverse impact.

It is concluded here that in order for us to use the term biological pollutants/pollution, we have to further define and assess the presence of a reduction in the integrity or damage at one or more levels of biological organisation (cell, individual, population, community and ecosystem). It is the view here that there is no need for new terms and definitions but that we should be clearer in those presently used.

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