Marine Pollution Bulletin 74 (2013) 517–525

Contents lists available at SciVerse ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Evaluating legacy contaminants and emerging chemicals in marine environments using adverse outcome pathways and biological effects-directed analysis

Thomas H. Hutchinson [a,*], Brett P. Lyons [a], John E. Thain [a], Robin J. Law [b]

[a] Centre for Environment, Fisheries and Aquaculture Science, Weymouth Laboratory, Barrack Road, The Nothe, Weymouth, Dorset DT4 8UB, United Kingdom
[b] Centre for Environment, Fisheries and Aquaculture Science, Cefas, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 0HT, United Kingdom

ARTICLE INFO

Keywords:
Biomarkers
Bioassays
Chemical mixtures
Mode of action
Marine Strategy Framework Directive
Water Framework Directive

ABSTRACT

Natural and synthetic chemicals are essential to our daily lives, food supplies, health care, industries and safe sanitation. At the same time protecting marine ecosystems and seafood resources from the adverse effects of chemical contaminants remains an important issue. Since the 1970s, monitoring of persistent, bioaccumulative and toxic (PBT) chemicals using analytical chemistry has provided important spatial and temporal trend data in three important contexts; relating to human health protection from seafood contamination, addressing threats to marine top predators and finally providing essential evidence to better protect the biodiversity of commercial and non-commercial marine species. A number of regional conventions have led to controls on certain PBT chemicals over several years (termed 'legacy contaminants'; e.g. cadmium, lindane, polycyclic aromatic hydrocarbons [PAHs] and polychlorinated biphenyls [PCBs]). Analytical chemistry plays a key role in evaluating to what extent such regulatory steps have been effective in leading to reduced emissions of these legacy contaminants into marine environments. In parallel, the application of biomarkers (e.g. DNA adducts, CYP1A-EROD, vitellogenin) and bioassays integrated with analytical chemistry has strengthened the evidence base to support an ecosystem approach to manage marine pollution problems. In recent years, however, the increased sensitivity of analytical chemistry, toxicity alerts and wider environmental awareness has led to a focus on emerging chemical contaminants (defined as chemicals that have been detected in the environment, but which are currently not included in regulatory monitoring programmes and whose fate and biological impacts are poorly understood). It is also known that natural chemicals (e.g. algal biotoxins) may also pose a threat to marine species and seafood quality. Hence complex mixtures of legacy contaminants, emerging chemicals and natural biotoxins in marine ecosystems represent important scientific, economic and health challenges. In order to meet these challenges and pursue cost-effective scientific approaches that can provide evidence necessary to support policy needs (e.g. the European Marine Strategy Framework Directive), it is widely recognised that there is a need to (i) provide marine exposure assessments for priority contaminants using a range of validated models, passive samplers and biomarkers; (ii) integrate chemical monitoring data with biological effects data across spatial and temporal scales (including quality controls); and (iii) strengthen the evidence base to understand the relationship between exposure to complex chemical mixtures, biological and ecological impacts through integrated approaches and molecular data (e.g. genomics, proteomics and metabolomics). Additionally, we support the widely held view that (iv) that rather than increasing the analytical chemistry monitoring of large number of emerging contaminants, it will be important to target analytical chemistry towards key groups of chemicals of concern using effects-directed analysis. It is also important to evaluate to what extent existing biomarkers and bioassays can address various classes of emerging chemicals using the adverse outcome pathway (AOP) approach now being developed by the Organization for Economic Cooperation and Development (OECD) with respect to human toxicology and ecotoxicology.

1. Introduction

Across the modern world, synthetic chemicals have become central to food production, drinking water disinfection, drug discovery, family planning and in a wide range of manufacturing industries. It is also striking that the pace of chemical discovery

* Corresponding author. Tel.: +44 (1305)206600; fax: +44 (1305)206601.
E-mail address: tom.hutchinson@cefas.co.uk (T.H. Hutchinson).

0025-326X/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2013.06.012

is growing rapidly, with the Chemicals Abstracts Service (CAS REGISTRY) reporting in May 2011 registration of the 60 millionth chemical substance. Coming after the CAS REGISTRY crossed the 50 million substance registration in only 2009, this second major milestone showed the continued acceleration of synthetic chemical innovation globally (CAS, 2011). Historically, the development of sensitive analytical monitoring methods has shown the potential for synthetic and natural chemicals (e.g. metals) to enter marine ecosystems as a result of human activities, in some cases being linked with adverse health impacts on marine species or seafood supplies (Clark et al., 1997; Walsh et al., 2008). Protecting marine ecosystems and food resources from the adverse effects of chemical contaminants remains an important goal, reflecting one key aspect of the socio-economic value of the coastal zones (Martínez et al., 2007) and oceans (Costanza, 1999). The Millennium Ecosystem Assessment (2005) noted the important impact of marine pollution (including eutrophication) and subsequently there have been other estimates of economic losses resulting from marine pollution. For example, the environmental losses in Spain because of marine pollution from the *Prestige* oil spill were estimated to be 574 million Euros (Loureiro et al., 2009). Additionally, Cai and Li (2011) reported that the economic losses from marine pollution adjacent to the Pearl River estuary, China, were 5040 million US dollars per year (accounting for 16.5% of the total economic value of the marine ecosystem). More recently, the 2010 oil spill from the *Deepwater Horizon* disaster currently has total estimated costs of $37.2 billion (BBC, 2012), although others suggest costs could be up to $63 billion (Wall Street Journal, 2010).

In a number of global areas, the monitoring of persistent, bioaccumulative and toxic (PBT) chemicals using analytical chemistry has provided important spatial and temporal trend data for several decades under the auspices of OSPAR (Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic) and other regional conventions. A step-change in public and scientific concerns regarding chemical pollution of the ocean occurred in the 1970s with the outbreak of Minamata disease, where eating of methylmercury contaminated shellfish in Minimata Bay, Japan, led to mass poisoning of the local population that was traced to effluent releases from a chemical factory (Harada, 1995). This was followed by the raising of awareness of the hazards of dumping of wastes at sea, most notably by non-governmental organisations in relation to radioactive materials (e.g. Ringius, 2000), and also studies on the bioaccumulation of persistent organochlorines in marine wildlife (e.g. Tanabe et al., 1994). Chemical monitoring data have proven to be important and useful in the contexts of human health protection from seafood contamination, in threats to marine top predators vulnerable to PBT chemicals, and also by giving essential evidence to protect ecosystems in terms of their species biodiversity and organism health (Walsh et al., 2008). For example, through the OSPAR Joint Assessment and Monitoring Programme (JAMP) and parallels under the Barcelona Convention (MEDPOL) and the Helsinki Commission (HELCOM), together with the 1972 Stockholm Convention on controlling Persistent Organic Pollutants (POPs) and other initiatives, the historic spotlight of concern has focussed on certain priority metals and organic chemical contaminants (e.g. cadmium, mercury and organic mercury compounds, polycyclic aromatic hydrocarbons [PAHs], polychlorinated biphenyls [PCBs], etc.). In Europe, these PBT chemicals are often referred to as 'legacy contaminants' in the contexts of the Marine Strategy Framework Directive and the Water Framework Directive (EEA, 2011; ESF, 2011). Integrated with chemical monitoring, evaluation of the biological effects in fish and other marine species of such legacy contaminants has also been a major activity in Europe in recent years (e.g. Matthiessen and Law, 2002; Thain et al., 2008; Law et al., 2010; Lyons et al., 2010). For example, for the United Kingdom (UK), recent evidence indicated marked reductions in North Sea contaminant loads resulting from certain legacy contaminants (e.g. cadmium, mercury, lindane and PCBs) (Defra, 2010). However, this has not resulted in a continuing decline in PCB concentrations in the blubber of harbour porpoises around the UK – as an example. An earlier decline in PCB concentrations following regulation, in place from 1981, has now stalled, with toxicologically significant concentrations in many animals (Law et al., 2012). Additionally, reflecting the neurotoxic mode of action (MOA) of certain PBT chemicals such as organochlorine insecticides, there is also recent evidence from North America that *p,p'*-DDT (and it's metabolite *p,p'*-DDE) can contribute to health effects in aquatic animals when co-exposed to the natural neurotoxin domoic acid (Tiedeken and Ramsdell, 2009 & Tiedeken and Ramsdell, 2010). The implications of such interactions between domoic acid impacts and latent xenobiotic residues in marine animals in Europe remain unstudied to our knowledge (Hall and Frame, 2010).

More recently, the steadily increasing sensitivity of analytical chemistry, growing databases on aquatic toxicity and other wider factors has led to a growing scientific focus on emerging chemical contaminants (sometimes termed 'non-regulated chemicals') in both marine and freshwater environments around the world (Richardson et al., 2005; Field et al., 2006; Andresen et al., 2007; Balaam et al., 2009; Jörundsdóttir et al., 2009; Arp, 2012). In Europe, emerging contaminants are often defined as chemicals that have been detected in the environment, but which are currently not included in routine monitoring programmes at the EU level and whose fate, behaviour and toxicological impacts are poorly understood (la Farré et al., 2008). There are no strict boundaries to the groups of chemicals often discussed in this context, with notable examples including brominated flame retardants (Covaci et al., 2011; Papachlimitzou et al., 2012), industrial chemicals (Wolschke et al., 2011), microplastics (Cole et al., 2011), nanomaterials (Farkas et al., 2010; Zhu et al., 2011) perfluorinated compounds (Haug et al., 2010; Houde et al., 2011), personal care products (Brausch and Rand, 2011), recreational drugs (Langford et al., 2011; Reid et al., 2011) and medicinal pharmaceuticals (Weigel et al., 2002; Roberts and Bersuder, 2006; Benotti and Brownawell, 2007; Madureira et al., 2010; Claessens et al., 2013).

2. Ecosystem integration of chemical & biological evidence

While chemistry and biology data are essential in distinguishing between chemical contamination and pollution (Chapman, 2007), it is widely recognised there are significant scientific and financial challenges in applying analytical chemistry to assess the spatial and temporal trends of large numbers of emerging contaminants (Coquery et al., 2005; Law et al., 2010; Laane et al., 2012). Enhanced chemical monitoring methods such as passive sampling can, however, play a beneficial role in the evaluation of legacy contaminants, emerging chemicals and natural toxins and also allow comparisons with the potential for bioaccumulation in marine fauna (Namieśnik et al., 2005; Fux et al., 2009). Progress on the further integration of chemical and biological assessment techniques for marine environments is described by Thain et al. (2008), represented in Fig. 1. A key element in this integrated process is the development and application of assessment criteria and this has been advanced with the recent development of assessment criteria for biological effect techniques, (see ICES/OSPAR, 2011).

Taking Europe as an example, this ecosystem approach is being taken forward in principle under the Marine Strategy Framework Directive (MSFD; (2008/56/EC) which has the overall objective of achieving or maintaining Good Environmental Status (GES) in Europe's seas by 2020. Eleven high-level qualitative Descriptors of Good Environmental Status have been defined in Annex 1 of the