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The role of natural science collections in the biomonitoring of environmental contaminants in apex predators in support of the EU's zero pollution ambition

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Abstract

The chemical industry is the leading sector in the EU in terms of added value. However, contaminants pose a major threat and significant costs to the environment and human health. While EU legislation and international conventions aim to reduce this threat, regulators struggle to assess and manage chemical risks, given the vast number of substances involved and the lack of data on exposure and hazards. The European Green Deal sets a '*zero pollution ambition for a toxic free environment*' by 2050 and the EU Chemicals Strategy calls for increased monitoring of chemicals in the environment. Monitoring of contaminants in biota can, inter alia: provide regulators with early warning of bioaccumulation problems with chemicals of emerging concern; trigger risk assessment of persistent, bioaccumulative and toxic substances; enable risk assessment of chemical mixtures in biota; enable risk assessment of mixtures; and enable assessment of the effectiveness of risk management measures and of chemicals regulations overall. A number of these purposes are to be addressed under the recently launched European Partnership for Risk Assessment of Chemicals (PARC). Apex predators are of particular value to biomonitoring. Securing sufficient data at European scale implies large-scale, long-term monitoring and a steady supply of large numbers of fresh apex predator tissue samples from across Europe. Natural science collections are very well-placed to supply these. Pan-European monitoring requires

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effective coordination among field organisations, collections and analytical laboratories for the flow of required specimens, processing and storage of specimens and tissue samples, contaminant analyses delivering pan-European data sets, and provision of specimen and population contextual data. Collections are well-placed to coordinate this. The COST Action *European Raptor Biomonitoring Facility* provides a well-developed model showing how this can work, integrating a European Raptor Biomonitoring Scheme, Specimen Bank and Sampling Programme. Simultaneously, the EU-funded LIFE APEX has demonstrated a range of regulatory applications using cutting-edge analytical techniques. PARC plans to make best use of such sampling and biomonitoring programmes. Collections are poised to play a critical role in supporting PARC objectives and thereby contribute to delivery of the EU's zero-pollution ambition.

Keywords: EU chemicals regulation, Zero pollution, Biomonitoring, Chemicals of emerging concern, Apex predator, Raptor, Marine mammal, Otter

Background

The chemical industry is the leading sector in the EU in terms of added value (€335.4 billion in 2018—Eurostat). The industry is a major employer, with 3.4 million jobs in the EU chemical industry and up to three times as many indirect jobs generated by the sector (Eurostat). Chemicals are used by industry, medicine, energy generation, agriculture and other sectors essential for maintaining health, nutrition and well-being. Chemical development, manufacture and use are important wealth generators, with global chemical production estimated to increase to USD 21,750 billion by 2060 (OECD 2019).

However, environmental contaminants pose a major threat to the environment and human health, exceeding the 'safe operating space' of the planetary boundary for 'novel entities' [1]. Tens of thousands of chemical substances are released into Europe's environment, of which large volumes are classified by Eurostat as hazardous to the environment or to human health. In 2020, the EU produced 78.9 million tonnes of chemicals hazardous to the environment, and 208.1 m tonnes hazardous to human health. However, the importance of chemical pollution is still highly understudied and undervalued in ecological research [2]. The increasing presence of synthetic chemicals in the environment imposes high costs. For example, the annual disease and dysfunction costs of human exposure to some of the most potent endocrine disrupting chemicals (EDCs) in the EU has been estimated at €157 billion (Trasande et al. 2015). The costs of harmful effects of chemicals on biodiversity and on ecosystem goods and services are difficult to assess given their complexity and, therefore, a weak scientific evidence base [3] but likely to be similarly vast.

EU legislation seeks to address this challenge, aiming to prevent and limit negative impacts of chemicals on human health and the environment. This includes directives and regulations on the safe marketing of industrial chemicals [4], plant protection products (PPPs) [5], biocidal products [6] and human and veterinary medicinal products [7–9], as well as environmental legislation like the Water Framework Directive (WFD) [10] and Marine Strategy Framework Directive (MSFD) [11], which aim to achieve a good environmental status, and the Environmental Liability Directive [12] . These are supplemented by global and regional conventions to which the EU, Member States and other European countries are party, such as the Helsinki Convention on the Baltic Sea (1992), OSPAR Convention on the NE Atlantic (1992), Stockholm Convention on persistent organic pollutants (2001) and Minamata Convention on mercury (Hg) (2013). However, in implementing these laws and conventions, regulators struggle to assess and manage chemical risks, given the vast number of substances involved and the lack of data on exposure and hazards.

The European Green Deal [13] acknowledges the continuing challenge presented by toxic substances in the environment, stating: '*Creating a toxic-free environment requires more action to prevent pollution from being generated as well as measures to clean and remedy it. To protect Europe's citizens and ecosystems, the EU needs to better monitor, report, prevent and remedy pollution from air, water, soil, and consumer products.*' The Green Deal sets a '*zero pollution ambition for a toxic free environment*' by 2050. To deliver on this ambition, the EC has published a Chemicals Strategy for Sustainability Toward a Toxic-Free Environment [14]. This states that: '*Monitoring the presence of chemicals in humans and ecosystems is key to improve the understanding of their impact… In partnership with Member States, the Commission will continue to foster research and (bio-) monitoring to understand and prevent chemicals-related risks and drive innovation in chemical risk assessment and regulatory science.*' Pollution is also mentioned in the EU Biodiversity Strategy to 2030 [14] as a key driver of biodiversity loss.

This paper explores the role of natural science collections (natural history museums, environmental specimen banks and other research collections) in the biomonitoring of environmental contaminants in apex predators in support of the EU's zero pollution ambition.

Main text

Monitoring of contaminants in biota (biomonitoring) aims to reveal the occurrence of chemical substances, residue concentrations, and predominant mixtures. Biomonitoring data can service a range of regulatory purposes, [15–19], including: (a) early warning of bioaccumulation of chemicals of emerging concern (CECs); (b) triggering of more rigorous risk assessments of persistent, bio accumulative and toxic (PBT) substances under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) [4] using a 'weight-of-evidence' approach; (c) substance assessment, development of guidance in relation to exposure and bioaccumulation and post-market vigilance under the EU plant protection products and biocidal products regulations [5, 6]; (d) risk assessment of chemical mixtures in biota—including aggregate, combined and cumulative exposures; (e) assessment of the effectiveness of chemical risk management measures under various EU regulations and international conventions, and of the effectiveness of chemicals regulations overall; (f) provision of exposure data for priority substances in top predators to provide a reality-check for calculated (theoretical) exposure values under the WFD [10] and MSFD (2008); (g) assessment of the quality of the marine environment under the Helsinki and Ospar Conventions; and (h) identification of potential endocrine disruptor chemicals (EDCs) and substances that are carcinogenic, mutagenic or toxic for reproduction (CMR) and of their potential health effects on biota, to inform species conservation under the EU Habitats and Birds Directives [20, 21].

A number of these purposes are to be addressed under the recently launched, €400 m, 7-year European Partnership for Risk Assessment of Chemicals (PARC) which aims to '*consolidate and strengthen the EU's research and innovation capacity for chemical risk assessment to protect human health and the environment and contribute to a non-toxic environment and a circular economy*' [22]. As part of its wide-ranging programme, PARC plans to make best use of existing sampling and biomonitoring programmes.

While most monitoring of chemicals in the environment focuses on water, sediment or on species at low trophic levels, species at higher trophic levels, notably apex predators, such as predatory birds and mammals, are of particular value to exposure assessment. Apex predators offer a number of advantages for the detection and interpretation of chemicals in the environment [19, 23, 24]: (1 occupying as they do high trophic levels, they integrate contamination across food webs, and across wide spatial scales (most apex predators have large feeding ranges and provide greater insight into persistence, bio-accumulation and (if monitored alongside co-occurring prey species biomagnification,(2 there is also a long history of ecotoxicological research on apex predators and many apex predator species have well-studied ecological traits, facilitating interpretation of detected contaminant residues; and (3 samples from apex predators are already available in many European sample collections and samples are added each year.. Key taxa for this purpose include seals and cetaceans for the marine environment, otters and piscivorous raptors for the freshwater environment, and raptors for the terrestrial environment as is being demonstrated by the LIFE APEX project (https://lifeapex.eu). By adding biomonitoring data from their prey sampled in a spatiotemporal context to the apex predators (e.g., fish prey of seals, otters and piscivorous raptors, bird or mammal prey of raptors), we can also better understand biomagnification of chemicals in food chains. In interpreting contaminant residues, attention must be paid to the resident or migratory behaviour of the species and individuals sampled [25, 26]—for this reason, Badry et al. [27] recommend the use of non-migratory raptors for pan-European contaminants monitoring.

Moreover, there is increasing interest in a 'One Health' approach which links wildlife, environmental and human health (WHO/SCBD 2015). There are important parallels between the increasing incidence of human disorders and those observed in wildlife [28],humans and wildlife share many targets for biologically active chemicals and adverse outcome pathways, so that innovative solutions for a pollution-free planet will protect both [29]. Using apex predators as a biomonitoring tool may be highly relevant in this context [17].

Securing sufficient environmental biomonitoring data at European scale, as called for in the EU Chemicals Strategy, implies large-scale, long-term monitoring. This in turn implies a steady supply of large quantities of fresh tissue samples of suitable species, at pan-European scale. The fact that most apex predators in Europe are protected species might seem to suggest such sample supply to be problematic as planned culling of individuals for this purpose is prevented by law, and is in any case not justifiable from an ethical viewpoint.

However, such culling is not necessary as a solution that does not involve killing wild animals is close at hand. Natural science collections across Europe—including natural history museums, environmental specimen banks, and other research collections—are very well-placed to supply the needed volume of fresh apex predator tissue samples on a sustained basis. This is because they: (a) are legally empowered to store samples from protected species; (b) regularly receive large numbers of fresh specimens of apex predators, including marine mammals, otters and raptors (for the latter, see Ramello

et al. 2022), that have been found dead in the field or have died in rehabilitation centres; (c) have, or can introduce, appropriate storage facilities (freezers); (d) have, or can gain, the necessary capacities to process and store samples for contaminant monitoring purposes; € have, or can adopt, existing protocols (e.g., Espin et al. 2016, 2020) for processing and storage of samples, using quality assurance and quality control procedures that support delivery of robust contaminant data; (f) are increasingly networked and coordinated for this purpose at pan-European scale (e.g., through the COST Action 'European Raptor Biomonitoring Facility'—https://erbfacility.eu); (g) are in general keen to enhance their societal relevance by supplying useful data; (h) are typically registered under the Convention on International Trade in Endangered Species (CITES), facilitating shipping of samples of CITES-listed species (which includes most apex predators) to laboratories; (i) work in the field and/or are well-connected to field organisations that can, if required, increase specimen supply and provide necessary contextual data; (j) are increasingly well-connected to analytical laboratories, (k) retain archives of examined specimens in long-term storage allowing for any retrospective contaminant studies; (l) are increasingly digitized allowing for timely knowledge of available samples (digitisation is being mainly promoted by the Distributed System of Scientific Collections—DiSSCo [30]).

Pan-European monitoring requires effective coordination and networking among field organisations, collections and analytical laboratories for: (a) the flow of the required specimens (and relevant specimen contextual data, such as the date of collection, location, cause of death, etc.) to collections; (b) the processing and storage of specimens and tissue samples therefrom following appropriate protocols; (c) contaminant analyses delivering pan-European data sets; and (d) provision of population contextual data, which allow correct interpretations of contaminant analysis data in assessing contaminant exposure and impact on target species populations [15]. Collections are well-placed between the field and analytical labs to coordinate the flow of animal specimens, tissue samples and related contextual specimen data [25, 26, 31].

The COST Action *European Raptor Biomonitoring Facility* (ERBFacility, 2017–22) [32], which built on the previous European Science Foundation networking programme *Research and Monitoring for and with Raptors in Europe* [33], provides a well-developed model showing how this coordination and networking can work, which could be replicated for other taxa (marine mammals, otters, selected prey species). It integrates: (1) a European Raptor Biomonitoring Scheme, which sets out priorities for which species and tissue matrices to analyse and the analytical methods and protocols to be used (see, e.g., [27], Espin et al. 2021); (2) a distributed European Raptor Specimen Bank, which brings together raptor collections across Europe and includes a European Raptor Sample Database of pertinent frozen raptor samples; and (3) a European Raptor Sampling Programme, which coordinates the gathering of specimens and relevant specimen and population contextual data to support interpretation of the results of chemicals analyses.

The COST Action has brought these three key elements together in an Integrated framework for a European Raptor Biomonitoring Facility [34] and delivered a proof of concept (analysing c. 450 tawny owl *Strix aluco* samples to elucidate spatial patterns for selected contaminants across Europe) (Lopez Antía et al. in prep.). However, continued funding will be required to establish this Facility and sustain it over the longer term to deliver the biomonitoring data continuously required under the EU Chemicals Strategy.

Simultaneously, the EU-funded project *Systematic use of contaminant data from apex predators and their prey in chemicals management*—LIFE APEX (2018–22) [35] has demonstrated a range of regulatory applications of biomonitoring in apex predator and prey samples using cutting-edge analytical techniques. It has analysed marine mammal and fish, otter and freshwater fish, and raptor samples.

One such application involves suspect screening (for presence/absence) of 65,000 + substances included in the NORMAN network SusDat database [36], and wide-scope target screening (providing residue concentrations) of > 2,400 known CECs, included in the target list of National and Kapodistrian University of Athens [37] to provide early warning of the presence of CECs in biota and identify predominant mixtures turning up in apex predators.

A second application uses the same data in combination with the JANUS tool to: (a) derive a short-list of substances to be considered (by ECHA and Member State competent authorities for chemicals) for prioritisation for further PBT assessment.

A third application involves exploring the extent to which we can use pooled apex predator (raptor) samples to detect whether the imposition of regulatory risk management measures (RMM) actually leads to the desired downward trend of real-world residue concentrations over time. By optimising the number of samples per pool to detect the desired downward trend, we can reduce the total number of analyses required while maintaining a representative sample, and thereby ensure cost-effective monitoring of effectiveness of RMM [38].

For all these important applications, the cost of biomonitoring is modest in relation to the potentially vast

cost savings to be realised by applying the data to reduce harmful effects of toxic substances and thereby improving wildlife and human health.

Conclusions

Natural science collections, in coordinating a steady, long-term, pan-European supply of apex predator (and prey) samples, and working in collaboration with field organisations, analytical laboratories and regulators through arrangements, such as the European Raptor Biomonitoring Facility, are poised to play a critical role in supporting PARC objectives—in particular relating to environmental monitoring and the development of an early warning system—and thereby contribute to delivery of the EU Chemical Strategy and the EU's zero-pollution ambition for a non-toxic environment.

Abbreviations

CEC: Chemical of Emerging Concern; CITES: Convention on Trade in Endangered Species; EC: European Commission; ECHA: European Chemicals Agency; EU: European Union; PARC: European Partnership for Risk Assessment of Chemicals; PBT: Persistent, bioaccumulative, and toxic; RMM: Risk management measure.

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Author contributions

PM: conceptualisation, writing—original draft, editing, funding acquisition. JK: conceptualisation, review and comment, funding acquisition. T: review and comment, funding acquisition. JS: review and comment, funding acquisition. GD: conceptualisation, writing—original draft, editing, funding acquisition. All others: review and comment. All authors read and approved the final manuscript.

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Competing interests

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