Environment International 67 (2014) 12–21

Contents lists available at ScienceDirect

Environment International

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

An overview of existing raptor contaminant monitoring activities in Europe

P. Gómez-Ramírez [a,*], R.F. Shore [b], N.W. van den Brink [c], B. van Hattum [d], J.O. Bustnes [e], G. Duke [f], C. Fritsch [g], A.J. García-Fernández [a], B.O. Helander [h], V. Jaspers [i,j], O. Krone [k], E. Martínez-López [a], R. Mateo [l], P. Movalli [d], C. Sonne [m]

[a] Department of Toxicology, Faculty of Veterinary Medicine, University of Murcia, Campus de Espinardo, 30100 Murcia, Spain
[b] NERC, Centre for Ecology and Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK
[c] Alterra, Wageningen UR, Box 47, NL-6700AA Wageningen, The Netherlands
[d] Institute for Environmental Studies, VU University, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands
[e] Norwegian Institute for Nature Research, FRAM—High North Research Centre on Climate and the Environment, NO-9296 Tromsø, Norway
[f] Environmental Change Institute, Oxford University Centre for the Environment, South Parks Road, Oxford OX1 3QY, UK
[g] Chrono-Environnement, UMR 6249, University of Franche-Comté -, CNRS, Usc INRA, Place Leclerc, F-25030 Besançon Cedex, France
[h] Swedish Museum of Natural History, Department of Contaminant Environmental Research & Monitoring, Box 50007, SE-104 05 Stockholm, Sweden
[i] Department of Biology, University of Antwerp, Universiteitsplein 1, 2610 Wilrijk, Belgium
[j] NTNU, Realfagbygget, DU2-169, Høgskoleringen 5, Trondheim 7491, Norway
[k] Leibniz Institute for Zoo and Wildlife Research, Alfred-Kowalke-Strasse 17, 10315 Berlin, Germany
[l] Instituto de Investigación en Recursos Cinegéticos (IREC), CSIC-UCLM-JCCM, Ronda de Toledo s/n, 13071 Ciudad Real, Spain
[m] Arctic Environment, Department of Bioscience, Aarhus University, Roskilde, Denmark

ARTICLE INFO

Article history:
Received 4 September 2013
Accepted 10 February 2014
Available online 13 March 2014

Keywords:
Contaminants
Biomonitoring
Raptors
Europe
Inventory

ABSTRACT

Biomonitoring using raptors as sentinels can provide early warning of the potential impacts of contaminants on humans and the environment and also a means of tracking the success of associated mitigation measures. Examples include detection of heavy metal-induced immune system impairment, PCB-induced altered reproductive impacts, and toxicity associated with lead in shot game. Authorisation of such releases and implementation of mitigation is now increasingly delivered through EU-wide directives but there is little established pan-European monitoring to quantify outcomes. We investigated the potential for EU-wide coordinated contaminant monitoring using raptors as sentinels. We did this using a questionnaire to ascertain the current scale of national activity across 44 European countries. According to this survey, there have been 52 different contaminant monitoring schemes with raptors over the last 50 years. There were active schemes in 15 (predominantly western European) countries and 23 schemes have been running for >20 years; most monitoring was conducted for >5 years. Legacy persistent organic compounds (specifically organochlorine insecticides and PCBs), and metals/metalloids were monitored in most of the 15 countries. Fungicides, flame retardants and anticoagulant rodenticides were also relatively frequently monitored (each in at least 6 countries). Common buzzard (*Buteo buteo*), common kestrel (*Falco tinnunculus*), golden eagle (*Aquila chrysaetos*), white-tailed sea eagle (*Haliaeetus albicilla*), peregrine falcon (*Falco peregrinus*), tawny owl (*Strix aluco*) and barn owl (*Tyto alba*) were most commonly monitored (each in 6–10 countries). Feathers and eggs were most widely analysed although many schemes also analysed body tissues. Our study reveals an existing capability across multiple European countries for contaminant monitoring using raptors. However, coordination between existing schemes and expansion of monitoring into Eastern Europe is needed. This would enable assessment of the appropriateness of the EU-regulation of substances that are hazardous to humans and the environment, the effectiveness of EU level mitigation policies, and identify pan-European spatial and temporal trends in current and emerging contaminants of concern.

1. Introduction

Biomonitoring studies using wildlife can provide an important source of information for understanding the potentially harmful effects of environmental contaminants, both in ecological receptors and in humans (Woodruff, 2011). Examples where similar detrimental effects

---

* Corresponding author. Tel.: +34 868887021; fax: +34 868884147.
E-mail address: pilargomez@um.es (P. Gómez-Ramírez).

http://dx.doi.org/10.1016/j.envint.2014.02.004

have been observed both in wildlife species and in humans include immune system impairment in black kites (*Milvus migrans*) (Blanco et al., 2004) and children (Lutz et al., 1999) due to exposure to cadmium or lead, and PCB-induced altered reproductive behaviour in glaucous gulls (*Larus hyperboreus*) (Bustnes et al., 2001) and neurological effects in children (Jacobson et al., 1990). Biomonitoring in wildlife, in fact, can serve as an early warning or sentinel of potential impacts in humans. For example, research on lead intoxication in white-tailed sea eagles (*Haliaeetus albicilla*) (Helander et al., 2009; Krone et al., 2003, 2009; Nadjafzadeh et al., 2013) highlighted the health risks for raptors and humans from consuming game meat in Germany and Sweden (Federal Institute for Risk Assessment Germany, 2011; Kneubuehl, 2011; NFA, 2012). Studies on lead intoxication in red kites (*Milvus milvus*) (Pain et al., 2007) highlighted similar risks in the UK which have subsequently been realised for people (Green and Pain, 2012; Pain et al., 2010).

The European Union (EU) has developed a range of policies and legislative instruments to address environmental contamination (Duke, 2008). This includes the relatively recent REACH directive (European Commission, 2006) and policies on persistent organic pollutants (European Commission, 2004, 2007), pesticides and biocides (European Commission, 2012). These instruments operate at an EU-wide scale to protect human health and the environment. A key issue with all such legislative instruments is to determine how effective they are. Measuring the numbers of registrations, authorisations and restrictions on chemicals only provides data on activities undertaken under the auspices of the EU directives. Such measures do not provide information on how effective the measures were in achieving mitigation targets—that requires monitoring. Direct monitoring of air, soil, water and sediments can be useful for determining the degree of contamination in a particular area, but does not provide a measure of bioavailability and resultant uptake by biota or people. It is only through direct biomonitoring (the analysis of contaminants in tissues of organisms) that the actual exposure of organisms can be properly determined and related to levels in the physical environment (Schubert, 1985). Furthermore, when biomonitoring is also designed to examine effects, new data are obtained on the possible detrimental effects of compounds on a range of species, including sensitive species and humans (García-Fernández and María-Mojica, 2000; NRC, 1991).

Biomonitoring is often carried out using proven sentinels of environmental contamination. The value of birds as biomonitors of environmental pollution has been broadly recognised (Grasman et al., 1998; Newton et al., 1993; Rattner, 2009; van Wyk et al., 2001). This is also evident from the establishment of several governmental monitoring programmes, such as the Trilateral Monitoring and Assessment Programme, the National Swedish Contaminant Monitoring Programme (Becker, 2003) and the Arctic Monitoring and Assessment Programme (AMAP). Amongst birds, raptors (birds of prey, owls and scavengers) are considered especially suitable for monitoring PBT (persistent, bioaccumulative, toxic) chemicals (e.g. Sergio et al., 2005, 2006), although the choice of species and associated traits (such as foraging in terrestrial or freshwater habitats) need to be matched to the fate pathways of the compounds of interest. There are a number of key characteristics that make raptors good sentinels for environmental contaminants. These include: position in food webs (often apex predators), relatively long lifespan over which to accumulate contaminants, integration of exposure both over time (Furness, 1993) and relatively large spatial areas, relative ease with which individuals (particularly nestlings) can be captured and non-destructive samples (blood, feather, preen gland oil) collected, and relative ease with which populations can be quantified and monitored. These criteria are all identified by the U.S. National Research Council as requirements for sentinel species (NRC, 1991). Raptors are also known to have measurable responses to PBT chemicals, ranging from residue accumulation to population decline. Indeed, it was the dramatic population declines observed in the bald eagle (*Haliaeetus leucocephalus*) in the basin of the Great Lakes in North America USA (Bowerman et al., 1995), the peregrine falcon (*Falco peregrinus*), eurasian sparrowhawk (*Accipiter nisus*) and golden eagle (*Aquila chrysaetos*) in the UK (Ratcliffe, 1970) and the white-tailed sea eagle in Sweden (Helander et al., 2008) that sparked awareness for the need to control the environmental release of several organochlorine compounds. This clearly demonstrated the value of raptors as powerful sentinels for environmental monitoring (Helander et al., 2008). In fact, the current ban under the Stockholm Convention on PCBs and other PBT compounds that are potentially harmful to both people and wildlife has been partly based on exposure and effects data in raptors (Rattner, 2009).

In Europe, there is a large number of biomonitoring programmes using raptors. However, only some are established at a national scale. They include the National Environment Monitoring Programme in Sweden (Helander et al., 2008), the Predatory Bird Monitoring Scheme (PBMS) in the United Kingdom (Walker et al., 2008), the Bird Monitoring Programme in Finland (Koskimies, 1989) and the Monitoring Programme for Terrestrial Ecosystems (TOV) in Norway (Gjershaug et al., 2008). However, these schemes are not linked, and so do not identify trends in contamination at the broader (European) spatial scale. Published papers and reports provide evidence that contaminant studies using raptors are also conducted in other EU countries, such as Spain, Germany, Belgium, Italy and The Netherlands (Gómez-Ramírez et al., 2011; Jaspers et al., 2006; Kenntner et al., 2003; Movalli et al., 2008b; van den Brink et al., 2003). However, these studies are typically limited in spatial extent and/or duration and are rarely repeated (García-Fernández et al., 2008). Overall therefore, there appears to be widespread capability and expertise to use raptors to monitor the effectiveness of EU directives at a pan-European scale. However, existing national and sub-national monitoring initiatives need to be reinforced and coordination at a pan-European scale improved (Movalli et al., 2008a).

The first requirement to assess the potential for EU-wide coordinated monitoring with raptors is the knowledge of the current scale of on-going monitoring activities. Indeed, it is possible that monitoring of some contaminants may already be sufficiently widespread to allow assessment of temporal and spatial trends at an EU scale. However, whether this is, in fact, the case is unknown because there is no EU-wide inventory of monitoring activity. For this reason, the aim of the present manuscript was to investigate the possibility of EU wide monitoring using raptors. This was done both by means of a questionnaire designed to elucidate current contaminant monitoring activities with raptors across Europe and by interpretation of the results during a workshop by relevant members of EURAPMON (Research and Monitoring for and with Raptors in Europe; http://www.eurapmon.net), a European Science Foundation Research Network.

2. Material and methods

A questionnaire template was designed based on the existing questionnaire used by the WILDCOMS network in the UK (http://www.wildcoms.org.uk/). This comprised an Excel document (Microsoft Office 2007) with questions gathered in five worksheets (Table S1 in Supplementary material). The majority of questions were closed in nature, since they provide a greater uniformity of responses and are more easily processed than open-ended questions, where the respondent provides free text answers (Babbie, 2013). The first worksheet contained questions regarding the metadata of the scheme, for instance the name of scheme or project, the year it started, the duration and the species monitored. In the subsequent worksheets, the questions focused on the main aims of the monitoring projects, the type of samples collected, types of contaminants determined, and how the results of the projects were disseminated.

A mailing list of 62 researchers engaged in biomonitoring environmental pollutants with raptors in Europe was compiled using a contact database established by EURAPMON, or by directly contacting researchers identified from their peer-reviewed research articles or internet sites. Additionally, 134 other researchers identified through the EURAPMON network as potentially working on monitoring of contaminants with raptors were contacted by e-mail to inform them about the questionnaire and requesting that they provide contact details for researchers who were conducting biomonitoring studies with raptors. Overall, 59 researchers from a total of 44 European countries (plus Israel), ranging from Portugal in the west, Italy in the South, Ukraine in the East and Norway in the North, were contacted.

To assess whether there was a trait bias in the birds that were included in the monitoring schemes, we created a database in which major traits (prey spectrum, habitat type, migration behaviour, life expectancy) were quantified in a binary way (Table S2 in Supplementary material). Assignment of traits was based on ecological information available from general handbooks (i.e. Del Hoyo et al., 1994, 1999; Glutz von Blotzheim et al., 1971, 1980) and, in some cases, from species monographs (Table S3). This database was used to cluster the species by species traits, using the programme GenStat 14. We assessed how many monitoring schemes were included in each cluster. This analysis was intended to provide insights into which species traits were commonly included in the monitoring schemes.

3. Results and discussion

In total, we received 35 responses to our questionnaire, with a response rate of 59% which is considered good for analysing and reporting questionnaire data (Babbie, 2013). The responses indicated that, over the last 50 years, a total of at least 52 different contaminant monitoring schemes with birds of prey have been undertaken in 15 of the 44 (34%) countries surveyed; Sweden, Germany and Italy had the highest number (Table 1). The countries that undertake monitoring of contaminants in raptors are predominantly in Western Europe (Fig. 1).

Biomonitoring of contaminants was the main purpose of most studies (n = 49, 94%). However, many schemes had multiple functions. Other major aims were stated to be: analysis of factors that influence exposure (n = 29; 56%); detection and reporting of high levels of contaminants in the environment (n = 23; 44%); study of effects on health (n = 21, 40%), indicators of disasters (n = 16, 31%); biomarkers research (n = 14, 27%); and toxicokinetic studies (n = 4, 8%). Some of the general characteristics of the schemes are summarised in Table 1. Schemes were roughly equally split as to whether they used passive sampling – opportunistically collecting birds found dead (and may have died from a variety of causes) – and/or active sampling, where species were actively targeted and sampling campaigns were planned. Whilst samples were typically collected by project staff, particularly where schemes involved active sampling, approximately three quarters of schemes also used volunteers. This demonstrates the reliance on, and active engagement of, citizen science for this type of monitoring across Europe. Collected samples were archived for further analysis by 77% of schemes. Most schemes have been funded by public institutions which were the only source of funding for half the schemes, but 35% of schemes also obtained funding from private organisations and 15% of schemes were exclusively funded from the private sector. Most schemes published the results of their monitoring in research articles (83%) and/or reports (71%). A third of schemes posted data on websites and 12% published their results in books.

The compounds that were measured by the greatest number of schemes were the legacy persistent organic pollutants (POPs), specifically organochlorine insecticides (n = 42) and PCBs (n = 41), and metals–metalloids (n = 37) (Table S4). These compounds have been analysed in the majority of the 15 countries in which monitoring has been carried out (Fig. 2). Fungicides, molluscicides, flame retardants and anticoagulant rodenticides have been measured in more than half of the countries in which monitoring is carried out (Fig. 2) but the number of schemes which monitor for these compounds (9, 9, 21 and 14 projects, respectively) is less than for legacy POPs and metals–metalloids (Table S4). This may be because concerns about the environmental presence and effects of these newer compounds have been recognised only relatively recently and so there has been less time in which to initiate monitoring in many countries. There were also a number of schemes (n = 13) that monitored other compounds not specifically listed in the questionnaire (mostly perfluorinated compounds (PFCs), barbiturates, dioxins and furans). PFCs were only measured in Denmark, Norway and Belgium, whilst dioxins and furans were only monitored in Sweden and Finland. Of the remaining less persistent compounds, only the UK and southern European countries (Spain, Portugal, France) measure a wide variety (PAHs, nematicides, other vertebrate control compounds, pharmaceuticals, barbiturates, acaricides and herbicides) (Table S4). This diversity may be because monitoring is conducted in these countries for substances used in illegal poisonings. In contrast, schemes in some countries measure very few or only single suites of compounds in raptors; for instance, Ireland monitors only anticoagulant rodenticides and Switzerland only metals.

Time-series studies provide information not only for assessing the risk of chemicals but also for evaluating the success of any regulatory action to reduce emissions (Bignert et al., 2004). The duration and frequency of monitoring can be critical factors that influence the statistical power to detect temporal changes in contamination (Bignert, 2002; Bignert et al., 2004; Riget et al., 2000), particularly decline in PBT compounds. This is because these compounds, by definition, degrade relatively slowly, and detection of small annual declines in environmental concentrations requires a relatively large number of replicate (annual) measurements (Shore et al., 2005). For example, it took between 13 and 21 years of annual monitoring to detect statistically significant declines in liver concentrations of dieldrin, DDT and mercury in the Eurasian sparrowhawk in the UK (Shore et al., 2005). The current survey has demonstrated that the earliest monitoring programmes in Europe were started in the late 1950s and early 1960s in Finland, Sweden and the UK and, in total, 23 schemes (46%) have been undertaken for more than 20 years. Most monitoring schemes have been conducted for at least 5 years (Table 1) and some of those that have been running for shorter periods have only recently started but remain ongoing. Thus, there is a significant number of established, long term monitoring studies in Europe which could potentially be used to assess time trends in contaminant concentrations in birds.

The 52 monitoring schemes have measured contaminants in a variety of different matrices. Choice of matrix may depend upon the aims of the scheme as various tissues can have very different rates of accumulation and elimination, and so provide information of accumulation over different time scales and/or time periods (Bignert et al., 2004). Non-invasive and/or non-destructive samples (feathers, abandoned/addled eggs, blood) were amongst the types of samples collected most frequently (Fig. 3), reflecting the importance of practical, ethical and conservational issues when sampling raptors. Moreover, feathers and eggs were the commonest types of sample collected across Europe (Fig. 3). The frequency of collection of feathers most probably reflects that they can be easily found in nests or collected during ringing activities, can be easily stored, and are of use for both proactive and passive monitoring as they can be obtained from either live or dead birds. Furthermore, an increasing number of studies indicate that it is possible to correlate levels of organochlorines and metals in feathers with concentrations in blood and internal tissues (Burger, 1993; Dauwe et al., 2005; Espín et al., 2012; Jaspers et al., 2006; Martínez-López et al., 2004) although there is some concern about time dependent processes in the deposition of contaminants in the feather (Bortolotti, 2010) and the influence of external contamination (Jaspers et al., 2007), which may hamper the interpretation of feather concentrations. Eggs have long been used for monitoring contaminants (Gómez-Ramírez et al., 2012; Helander et al., 2002; Mañosa et al., 2003; Mateo et al., 2000; Moore and Ratcliffe, 1962; Newton and Bogan, 1974; Walker et al., 2008) as they are a homogenous sample that can be directly related to reproductive effects and success and are also relatively easily collected both proactively and opportunistically. However, contaminant concentrations in eggs are the result of what has been transferred into the egg by the laying female and may not be indicative of exposure in other individuals (for example, males and juvenile birds) in the population. Furthermore, associations between contaminants in eggs and levels and patterns of

Table 1
Overview of monitoring schemes by country.

Country	# of monitoring schemes	Spp[a]	Strategy			First year sampling	Length scheme			Uses volunteers	Archive	# of compounds
			Active	Passive	Both		<5 years	>5 years	Intermittent			
Belgium	1	Ow	1	0	0	2012	1	0	0	1	1	4
Denmark	3	DR	2	0	1	1981	1	2	0	3	3	5
Finland	4	DR, Ow	1	3	0	1965	0	4	0	4	4	5
France	5	DR, Ow	1	1	3	1986	2	2	1	5	4	14
Germany	6	DR, Ow	0	5	1	1967	0	6	0	6	6	14
Ireland	1	DR, Ow	0	1	0	2011	1	0	0	0	1	1
Italy	6	DR, Ow	4	1	1	1991	0	1	5[b]	3	3	3
The Netherlands	1	Ow	1	0	0	2000	0	0	1[c]	0	0	3
Norway	5	DR, Ow	3	1	1	1986	3	2	0	4	1	7
Portugal	2	DR, Ow	1	0	1	1992	0	1	1	0	0	6
Slovenia	1	DR, Ow	0	1	0	1995	0	1	0	1	1	1
Spain	4	DR, Ow	0	1	3	1992	0	4	0	0	4	12
Sweden	8	DR, Ow	2	1	5	1957	2	6	0	8	8	8
Switzerland	1	DR, Ow	0	0	1	2010	1	0	0	1	1	1
United Kingdom	4	DR, Ow	1	3	0	1960	0	4	0	4	3	14
Total	52		17	18	17		11	33	8	40	40	

[a] DR: Diurnal raptors, Ow: Owls.
[b] Four studies were one -off and one intermittent.
[c] One-off study.

contaminants in the maternal bird have largely been based on lipophilic substances with relatively long physiological half-lives (for example see Crosse et al., 2012, 2013) whereas some of the emerging PBT contaminants, such as perfluorinated compounds, are more associated with protein than lipid. The relationship between concentrations in eggs and adult birds may vary markedly between different classes of compounds. Collection of whole blood, plasma or serum was less common than for feathers or eggs, presumably because it was mostly conducted only by those schemes undertaking proactive sampling. Preen oil can be also obtained from live or dead birds and five of the more recently started schemes collect it. As such, it may be an emerging and promising type of non-destructive sample that can be used to monitor trends in exposure to lipophilic compounds such as PCBs, PBDEs or organochlorine insecticides (Jaspers et al., 2011; van den Brink et al., 2003).

A variety of internal organs and tissues are also collected by monitoring schemes (Fig. 3). In decreasing order of frequency, these were: liver, kidney, muscle, fat, bone and brain. Other organs such as lung, spleen and pancreas were sampled by occasional schemes. Carcasses were mentioned as a sample type in 18 studies but it is likely that many studies that analysed internal tissues collected whole carcasses and subsequently excised multiple tissues. Other, usually invasive, samples that were collected were mainly related to quantifying dietary exposure. Gizzard or gastric content, crop or pellet content were collected by three studies. There was no obvious relationship between the types of samples collected and the duration of monitoring schemes, except that eggs appeared to be predominantly collected by long term (>5 years) rather than short term (<5 years in duration and one-off studies) schemes (Fig. 3). However, the relative use of feathers, blood, eggs and liver samples did not differ significantly between long- and short term schemes (Chi squared test: $\chi^2 = 2.91$, df $= 3$, P $= 0.41$). The lack of any such difference may be because long term surveys collect several types of samples (although two long-term schemes only collected eggs), and have either changed or increased the types of sample that they collect as they have matured. This may reflect incorporation of new contaminants into the analytical portfolio, requiring analysis of new matrices and, as relationships between concentrations between different matrices become better understood (Dauwe et al., 2000; García-Fernández et al., 2013; Meyer et al., 2009), additions or changes to the matrices that are analysed.

The selection of a species for monitoring can be influenced by factors such as abundance, geographical distribution, conservation status and availability of samples that may already be collected by other studies. In all, contaminants have been monitored in some 38 species across Europe (Table S5). The number of species studied in each country varied widely and was greatest in Spain (31 species), Germany (20 species), Finland (19 species) and the UK (17 species). Almost half of the monitoring schemes (48%) focused solely on diurnal raptors whereas owls and scavengers were generally studied in conjunction with diurnal raptors (owls and diurnal raptors in 27% of schemes, scavengers and diurnal raptors in 3.8% and diurnal raptors, owls and scavengers in 7.7% of studies).

Amongst the diurnal raptors and scavengers, the common buzzard and common kestrel (*Falco tinnunculus*), are the most frequently studied species (18 studies each), whilst golden eagle, white-tailed sea eagle and peregrine falcon (*F. peregrinus*) are monitored in 16, 16 and 15 schemes respectively. Of the owls, the tawny owl and the barn owl are also commonly studied (16 and 15 schemes respectively). All these species are widely distributed in Europe (IUCN, 2012) and have been monitored for contaminants in between 6 and 10 countries (Fig. 4). Other species that have been monitored in a similar number of countries (Fig. 4), albeit by fewer schemes, are Eurasian eagle owl (*Bubo bubo*) (9 countries), northern goshawk (*Accipiter gentilis*), Eurasian sparrowhawk, long-eared owl (*Asio otus*) (7 countries each) and osprey (*Pandion haliaetus*) (6 countries). Diet is another key factor that is thought to influence bioaccumulation of contaminants by predators; for example, accumulation of organochlorines tends to be higher in

Fig. 1. Map of European countries with monitoring programmes measuring contaminants in raptor samples.

species that predate birds (Jaspers et al., 2006; van Drooge et al., 2008), because birds are generally less able to metabolise organochlorines than mammals (Walker, 1983). Of the 12 most widely monitored species (Fig. 4), most are mixed feeders, often taking a mixture of mammalian, avian, fish and, in some cases, invertebrate prey, although sparrowhawks and peregrine falcons are avian specialists and ospreys are piscivorous.

To gain insight into whether monitoring programmes include raptors with different traits (diet, habitat preference, migratory habits), all of which may affect accumulation patterns, we created a database of traits (Table S2) and performed a cluster analysis (Fig. 5). This revealed that, based on the traits for diurnal birds of prey (Fig. 5a), the osprey and the long-legged buzzard (*Buteo lagopus*) are completely separated from the main cluster. This indicated that their life-history traits are not comparable with other raptors. In the main cluster for birds of prey, we find five species which stood-alone: common buzzard, Egyptian vulture (*Neophron percnopterus*), honey buzzard (*Pernis apivorus*), white-tailed sea eagle and common kestrel; and two clusters containing two species each: northern Goshawk with Eurasian sparrowhawk and Black-winged Kite (*Elanus caeruleus*) with Montagu's

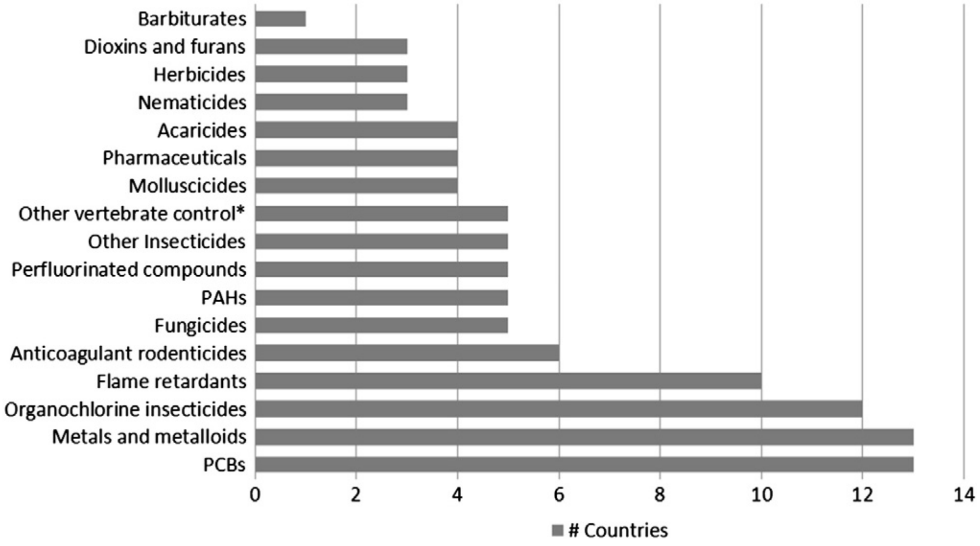

Fig. 2. Number of countries in which monitoring is carried out for different classes of compounds.

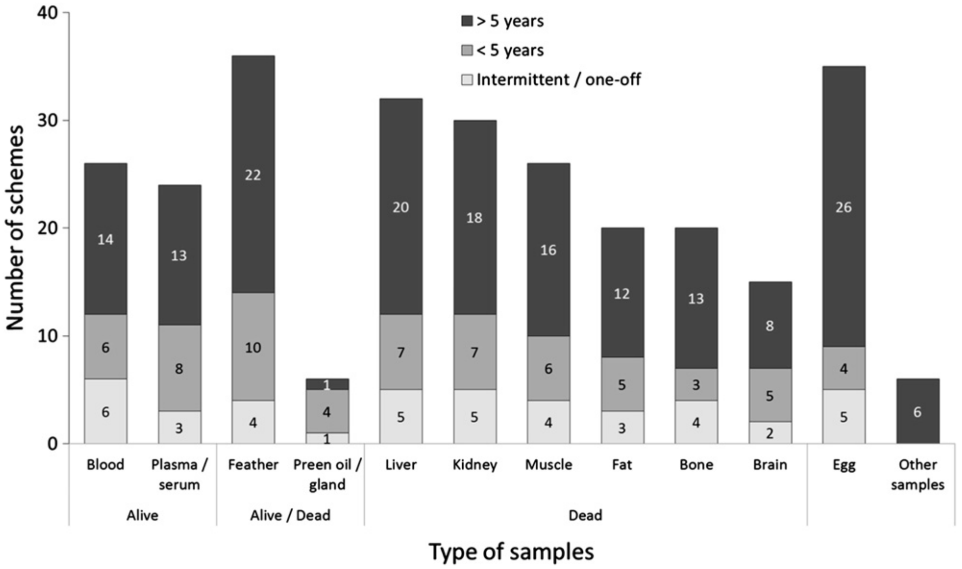

Fig. 3. Type of samples analysed in relation to length of studies, and whether they can be collected from live or dead birds. Numbers in bars indicate number of studies within each time category. "Other samples" include gizzard/crop content, pellets, lung, spleen and pancreas.

harrier (*Circus pygargus*). In the large sub-cluster, the Aquila-eagles and the large falcons (Hierofalcons) cluster together and were most closely related to the large vultures. For the owl cluster analyses, the scops owl (*Otus scops*) is completely separated from the main cluster and the eagle owl stands alone. On the other hand, the little owl (*Athene noctua*) and the barn owl cluster together in a different group than tawny owl, Tengmalm's owl (*Aegolius funereus*), ural owl (*Strix uralensis*), long-eared owl and short-eared owl (*Asio flammeus*). The grouping of birds of prey into clusters of similar life styles regarding food choice, habitat type and migration behaviour not only helps to understand similar patterns of accumulated contaminants but also provides a base to select one representative of a specific habitat or food web to study. Our questionnaire revealed that most species studied in Europe do not belong to a specific cluster but instead represent the biodiversity of birds of prey occurring in Europe.

One of the main reasons for conducting this questionnaire was to assess the potential for using raptors as sentinels for monitoring pan-European patterns and trends in environmental contaminants that pose risks to both wildlife and human health; such monitoring can be particularly valuable for assessing the impacts of mitigation measures. The questionnaire demonstrated that organochlorine compounds and toxic metals are currently the most frequently measured contaminants, reflecting the global concern about their health impacts. European legislation to ban the use of certain organochlorines, such as DDT, and the use of lead, both as an additive to gasoline and as shot for hunting over wetlands, would be expected to result in pan-European declines in environmental concentrations of these contaminants. A detailed meta-analysis of data from multiple schemes highlighted by our inventory is beyond the scope of the present paper but overviews indicate that residues of DDT and/or metabolites DDE and DDD have fallen in the eggs or tissues from raptors from South Greenland (Vorkamp et al., 2009), Spain (Hernández et al., 2008), Norway (Bustnes et al., 2007), Sweden (Roos et al., 2012), the UK (Newton, 1986) and Germany (Scharenberg and Looft, 2004). Likewise, monitoring lead in livers of kestrels from rural and city regions of south-eastern Spain and in feathers of tawny owls in Norway revealed a decline in residues following implementation of the European ban on lead additives in gasoline (Bustnes et al., 2013; Garcia-Fernandez et al., 2005). Monitoring with raptors can also indicate where and why legislation may be more limited in its effectiveness than originally anticipated. For example, some studies between the 1980s and 2000s found stabilising or even increasing concentrations of DDE in raptor eggs (Bustnes et al., 2007; García-Fernández et al., 2008; Gómez-Ramírez et al., 2012). This is thought to be due to local current environmental inputs of diphenylaliphatics such as dicofol (García-Fernández et al., 2008; Gómez-Ramírez et al., 2012; Martínez-López et al., 2007). Similarly, monitoring of white-tailed sea eagles in Sweden indicated that the impact of banning lead shot for shooting over wetlands was not as immediately effective as perhaps anticipated. The proportion of sea eagles that died from lead poisoning remained unchanged two years after the ban on use of lead shot (Helander et al., 2009), probably because lead from earlier use remains in the environment. Moreover, lead shot and bullets are still used for other types of hunting in most countries (Henny and Elliott, 2007) and lead may have also been used illegally.

The examples of DDT and lead demonstrate that the collated outputs from existing or past raptor monitoring can be used to evaluate, and with more detailed analysis, to quantify, the pan-European impact of mitigation measures implemented for some legacy POPs and toxic metals. Coordination and alignment of monitoring effort across Europe could similarly be used to track the effectiveness of bans on more recently used but restricted POPs, such as some of the polybrominated diphenyl ethers (e.g. van den Steen et al., 2009). Furthermore, such coordinated monitoring could also quantify the extent of, and temporal trends in, environmental contamination from pesticides, biocides, industrial compounds and potential endocrine disruptors that remain in use today. Such monitoring may not be restricted to measurement of chemical residues but could also encompass measurement of biomarkers of effect that are related to acute and/or chronic effects. One additional value of monitoring contaminant levels in raptors is that the populations of many raptor species are already being monitored for ecological and conservation reasons. This facilitates the collection of non-invasive samples and failed eggs for contaminant monitoring and also allows evaluation of whether variation in exposure to contaminants is likely to be linked to ecologically significant impacts, in terms of changes in population numbers.

In conclusion, this first pan-European inventory of contaminant monitoring using raptors has shown that there is an existing monitoring capability across multiple countries, although these are currently mostly in Western Europe. There is a homogeneity in generic monitoring approaches between monitoring schemes and it is likely that detailed

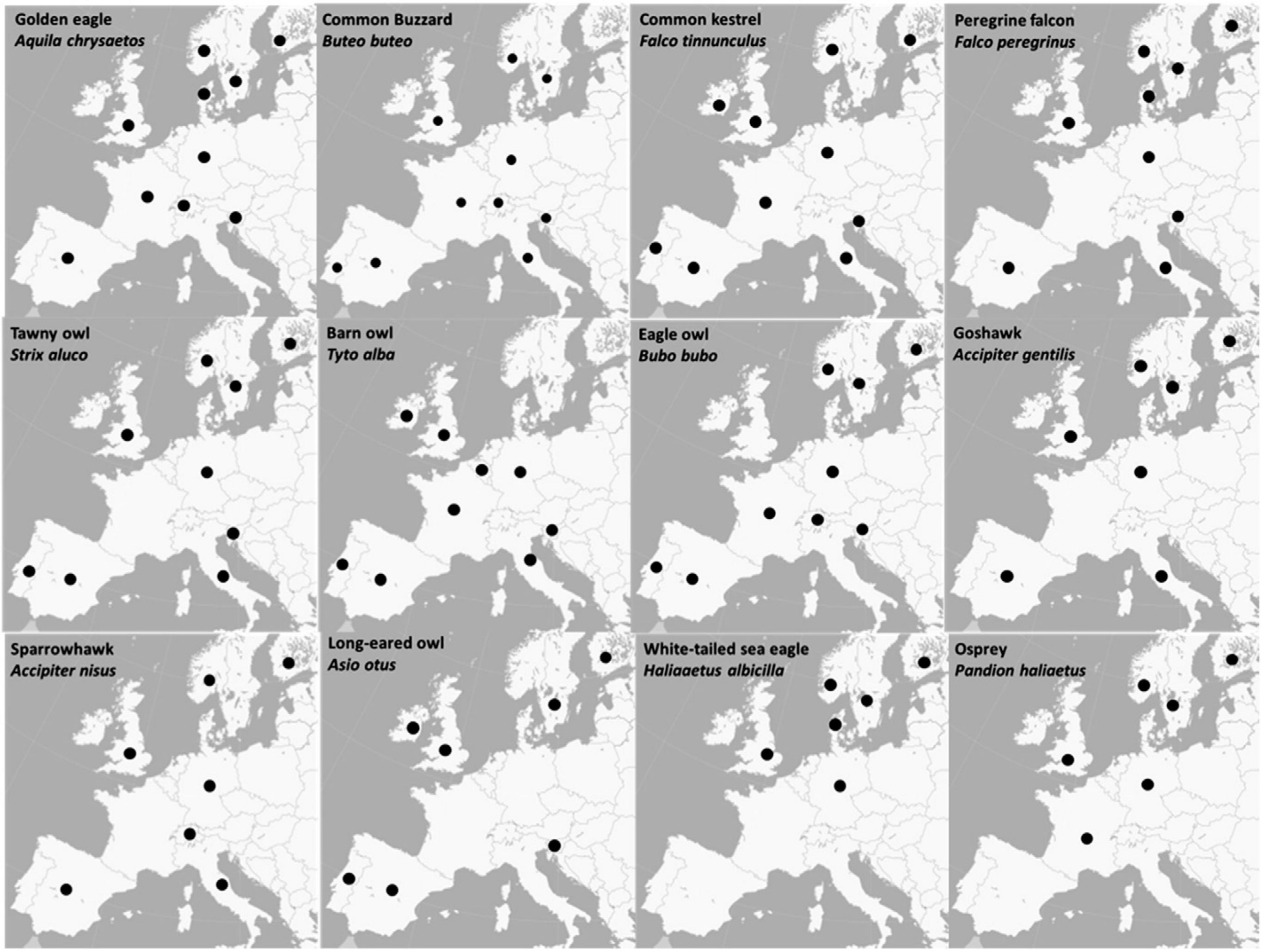

Fig. 4. Maps for the 12 species in which contaminants have been monitored most widely (number of countries) across Europe. Dots indicate countries in which contaminant monitoring has occurred. The position of dots within countries does not indicate the specific location of monitoring.

meta-analysis of time-trend data from multiple schemes is currently possible, at least to quantify temporal changes in contamination by legacy POPs. However, to develop effective pan-European monitoring, a network needs to be further developed between existing monitoring schemes so that activity could be harmonised in terms of species or species traits, sample matrix and contaminants studied and further research is needed to establish which matrices may be the most suitable for monitoring new and emerging POPs. Such a network would also need to encompass analysis of samples collected by ornithologists studying raptor populations in eastern European countries. The result of any such coordinated and strategic pan-European monitoring would be a capability to quantify large-scale spatial and temporal trends in exposure of wildlife sentinels to current and emerging contaminants of concern. Such coordinated monitoring would provide an unparalleled evidence base as to the scale, severity and likely impacts of environmental contamination, whether there is a need for Europe-wide mitigation, and the effectiveness of any mitigation. Such an evidence base should be a cornerstone for risk managers, policy makers and regulators to judge the effectiveness of EU directives, guide future pan-European actions, and identify any need for further policy or regulatory initiatives such as those being considered for endocrine disrupters (Abbas et al., 2013). Furthermore, this inventory offers an unmatched opportunity for developing a pan-European monitoring of raptor exposure to contaminants within the framework of the new paradigm of "adaptive monitoring" (Lindenmayer and Likens, 2009), a concept which has been shown to improve both management practices and strengthening of partnerships between researchers, policy-makers, and resource managers to reconcile policy-relevant and research-relevant goals (Lindenmayer et al., 2011).

Acknowledgements

This paper arises from work carried out by the EURAPMON Research Networking Programme which is funded by the European Science Foundation. EURAPMON provided an exchange grant to Dr. Pilar Gómez-Ramírez to investigate the state of current monitoring of contaminants with raptor activities in Europe and funded a workshop to analyse the results. We thank to all the investigators that contributed by completing the questionnaire. Thanks to MINECO for the financial support of the project CGL2011-16063-E.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2014.02.004.

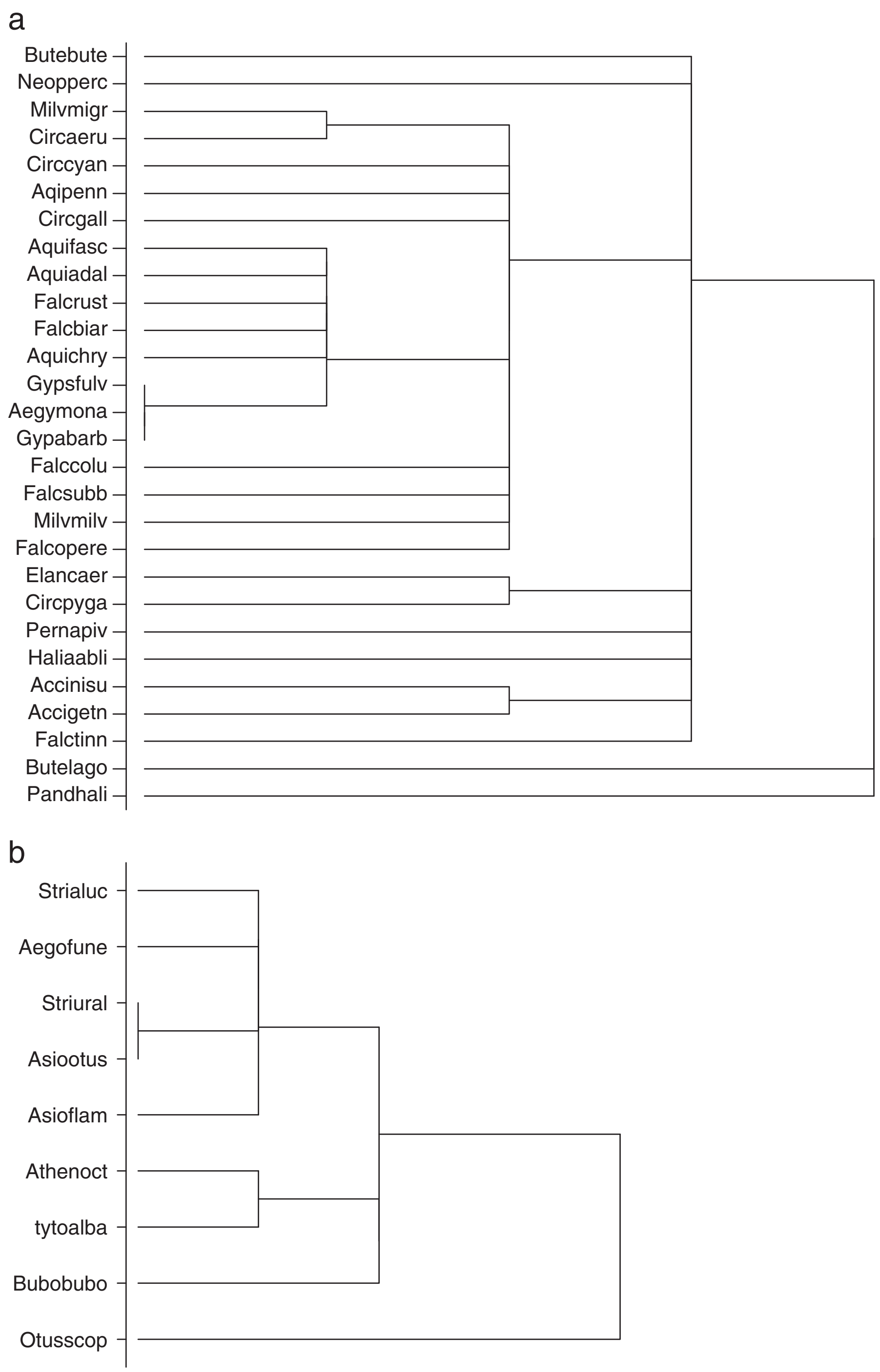

Fig. 5. Clustering of the birds of prey (a) and owls (b) according to their traits regarding feeding, habitat preferences and migratory habits. (a) Butebute: Common buzzard (*Buteo buteo*); Neopperc: Egyptian vulture (*Neophron percnopterus*); Milvmirg: Black kite (*Milvus migrans*); Circaeru: Marsh harrier (*Circus aeruginosus*); Circcyan: Hen harrier (*Circus cyaneus*); Aqipenn: Booted eagle (*Aquila pennata*); Circgall: Short-toed eagle (*Circaetus gallicus*); Aquifasc: Bonelli's eagle (*Aquila fasciata*); Aquidal: Imperial eagle (*Aquila adalberti*); Falcrust: Gyrfalcon (*Falco rusticolus*); Falcbiar: European lanner falcon (*Falco biarmicus*); Aquichry: Golden eagle (*Aquila chrysaetos*); Gypsfulv: Griffon vulture (*Gyps fulvus*); Aegymona: Black vulture (*Aegypius monachus*); Gypabarb: Bearded vulture (*Gypaetus barbatus*); Falccolu: Merlin (*Falco columbarius*); Falcsubb: Eurasian hobby (*Falco subbuteo*); Milvmilv: Red kite (*Milvus milvus*); Falcopere: Peregrine falcon (*Falco peregrinus*); Elancaer: Black-winged Kite (*Elanus caeruleus*); Circpyga: Montagu's harrier (*Circus pygargus*); Pernapiv: Honey buzzard (*Pernis apivorus*); Haliaabli: White-tailed sea eagle (*Haliaeetus albicilla*); Accinisu: Eurasian sparrowhawk (*Accipiter nisus*); Accigetn: Goshawk (*Accipiter gentilis*); Facltinn: Common kestrel (*Falco tinnunculus*); Butelago: Rough-legged buzzard (*Buteo lagopus*); Pandhali: Osprey (*Pandion haliaetus*). (b) Strialuc: Tawny owl (*Strix aluco*); Aegofune: Tengmalm's owl (*Aegolius funereus*); Striural: Ural owl (*Strix uralensis*); Asiootus: Long-eared owl (*Asio otus*); Asioflam: Short-eared owl (*Asio flammeus*); Athenoct: Little owl (*Athene noctua*); Tytoalba: Barn owl (*Tyto alba*); Bubobubo: Eagle owl (*Bubo bubo*); Otusscop: Scops owl (*Otus scops*).

References

Abbas A, Ahrens L, Andersson AM, Andersson P, Barra R, van Bavel B, et al. The Berlaymont Declaration on Endocrine Disrupters, Downloaded 10 June 2013. from: http://www.brunel.ac.uk/__data/assets/pdf_file/0005/300200/The_Berlaymont_Declaration_on_Endocrine_Disrupters.pdf.

Babbie E. The practice of social research. Wadsworth Cengage LearningUSA: Wadsworth Cengage Learning; 2013.

Becker PH. Biomonitoring with birds. In: Markert BA, Breure AM, Zechmeister HG, editors. Bioindicators and biomonitors: principles, concepts, and applications. Oxford: Elsevier; 2003. p. 677–736.

Bignert AICES Mar Sci Symp 2002;215:195–201.

Bignert A, Riget F, Braune B, Outridge P, Wilson S. Recent temporal trend monitoring of mercury in Arctic biota—how powerful are the existing data sets? J Environ Monit 2004;6(4):351–5.

Blanco G, Jiménez B, Frías O, Millan J, Dávila JA. Contamination with nonessential metals from a solid-waste incinerator correlates with nutritional and immunological stress in prefledgling black kites (*Milvus migrans*). Environ Res 2004;94(1): 94–101.

Bortolotti GR. Flaws and pitfalls in the chemical analysis of feathers: bad news–good news for avian chemoecology and toxicology. Ecol Appl 2010;20(6):1766–74.

Bowerman WW, Giesy JP, Best DA, Kramer VJ. A review of factors affecting productivity of bald eagles in the Great Lakes region: implications for recovery. Environ Health Perspect 1995;103(Suppl. 4):51–9.

Burger J. Metals in avian feathers: bioindicators of environmental pollution. Rev Environ Toxicol 1993;5:203–311.

Bustnes JO, Bakken V, Erikstad KE, Mehlum F, Skaare JU. Patterns of incubation and nest-site attentiveness in relation to organochlorine (PCB) contamination in glaucous gulls. J Appl Ecol 2001;38:791–801.

Bustnes JO, Bårdsen BJ, Bangjord G, Lierhagen S, Yoccoz N. Temporal trends (1986–2005) of essential and non-essential elements in a terrestrial raptor in northern Europe. Sci Total Environ 2013:458–60. [101–106].

Bustnes JO, Yoccoz NG, Bangjord G, Polder A, Skaare JU. Temporal trends (1986–2004) of organochlorines and brominated flame retardants in Tawny owl eggs from Northern Europe. Environ Sci Technol 2007;41:8491–7.

Crosse JD, Shore RF, Wadsworth RA, Jones KC, Pereira MG. Long term trends in PBDEs in sparrowhawk (*Accipiter nisus*) eggs indicate sustained contamination of UK terrestrial ecosystems. Environ Sci Technol 2012;46:13504–11.

Crosse JD, Shore RF, Jones KC, Pereira MG. Key factors affecting liver PBDE concentrations in sparrowhawks (*Accipiter nisus*). Environ Pollut 2013;177:171–6.

Dauwe T, Bervoets L, Blust R, Pinxten R, Eens M. Can excrement and feathers of nestling songbirds be used as biomonitors for heavy metal pollution? Arch Environ Contam Toxicol 2000;39:541–6.

Dauwe T, Jaspers V, Covaci A, Schepens P, Eens M. Feathers as a nondestructive biomonitor for persistent organic pollutants. Environ Toxicol Chem 2005;24(2):442–9.

Del Hoyo J, Elliot A, Sargatal J, [Hrsg.] 1994. Handbook of the birds of the world. New World vultures to guineafowl. [Vol. 2], Lynx Ed., Barcelona.

Del Hoyo J, Elliot A, Sargatal J, [Hrsg.] 1999. Handbook of the birds of the world. Hummingbirds to Barn owls. [Vol. 5], Lynx Ed., Barcelona.

Duke G. The EU environmental policy context for monitoring for and with raptors in Europe. Ambio 2008;37(6):397–400.

European Commission. Regulation (EC) No 850/2004 of the European Parliament and of the Council of 29 April 2004 on Persistent Organic Pollutants and amending Directive 79/117/EC. European CommissionEuropean Commission; 2004.

European Commission. Regulation (EC) No. 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH); 2006.

European Commission. Community Implementation Plan for the Stockholm Convention on Persistent Organic Pollutants. European Commission, Staff Working Document SEC(2007) 341; 2007.

European Commission. Regulation (EC) No. 528/2012 of the European Parliament and of the Council concerning the making available on the market and use of biocidal products (repealing and replacing Directive 98/8/EC; entry into force: 1 September 2013); 2012.

Espín S, Martínez-López E, Gómez-Ramírez P, María-Mojica P, García-Fernández AJ. Razorbills (*Alca torda*) as bioindicators of mercury pollution in the southwestern Mediterranean. Mar Pollut Bull 2012;64(11):2461–70.

Federal Institute for Risk Assessment Germany. Lead fragments in game meat can be an added health risk for certain consumer groups. Press release 32/2011 of 19.09.2011, Berlin, Germany. http://www.bfr.bund.de/en/press_releases_2011.html, .

Furness RW. Birds as monitors of pollutants. In: Furness RW, Greenwood JJD, editors. Birds as monitors of environmental change. London: Chapman and Hall; 1993. p. 86–143.

García-Fernández AJ, Romero D, Martínez-López E, Navas I, Pulido M, María-Mojica P. Environmental lead exposure in the European kestrel (Falco tinnunculus) from Southeastern Spain: the influence of leaded gasoline regulations. Bull Environ Contam Toxicol 2005;74:314–9.

García-Fernández AJ, Calvo JF, Martínez-López E, María-Mojica P, Martínez JE. Raptor ecotoxicology in Spain: a review on persistent environmental contaminants. Ambio 2008;37:432–9.

García-Fernández AJ, María-Mojica P. Contaminantes ambientales y su repercusión sobre la fauna silvestre. In: Ministerio de Agricultura, P.y.A., editors. Globalización medioambiental. Perspectivas agrosanitarias y urbanas; 2000. p. 215–27. [in Spanish].

García-Fernández AJ, Espín S, Martínez-López E. Feathers as a biomonitoring tool of polyhalogenated compounds: a review. Environ Sci Technol 2013;47:3028–43.

Gjershaug JO, Kålås J, Nygård T, Herzke D, Folkestad AO. Monitoring of raptors and their contamination levels in Norway. Ambio 2008;37(6):420–4.

Glutz von Blotzheim UN, Bauer KM, Bezzel E. Handbuch der Vögel Mitteleuropas. Akademische Verlagsgesellschaft, Frankfurt am Main, Vol. 4; 1971.

Glutz von Blotzheim UN, Bauer KM, Bezzel E. Handbuch der Vögel Mitteleuropas. Akademische Verlagsgesellschaft, Frankfurt am Main, Vol. 9; 1980.

Gómez-Ramírez P, Martínez-López E-, García-Fernández AJ, Zweers AJ, van den Brink NW. Organohalogen exposure in a Eurasian Eagle owl (*Bubo bubo*) population from Southeastern Spain: temporal–spatial trends and risk assessment. Chemosphere 2012;88: 903–11.

Gómez-Ramírez P, Martínez-López E, María-Mojica P, León-Ortega M, García-Fernández A. Blood lead levels and δ-ALAD inhibition in nestlings of Eurasian Eagle Owl (*Bubo bubo*) to assess lead exposure associated to an abandoned mining area. Ecotoxicol 2011;20: 131–8.

Grasman KA, Seanlon PF, Fox GA. Reproductive and physiological effects of environmental contaminants in fish-eating birds of the Great Lakes: a review of historical trends. Environ Monit Assess 1998;53:117–45.

Green RE, Pain DJ. Potential health risks to adults and children in the UK from exposure to dietary lead in gamebirds shot with lead ammunition. Food Chem Toxicol 2012;50: 4180–90.

Helander B, Axelsson J, Borg H, Holm K, Bignert A. Ingestion of lead from ammunition and lead concentrations in white-tailed sea eagles (*Haliaeetus albicilla*) in Sweden. Sci Total Environ 2009;407(21):5555–63.

Helander B, Bignert A, Asplund L. Using raptors as environmental sentinels: monitoring the White-tailed Sea Eagle *Haliaeetus albicilla* in Sweden. Ambio 2008;37(6):425–31.

Helander B, Olsson A, Bignert A, Asplund L, Litzén K. The role of DDE, PCB, coplanar PCB and eggshell parameters for reproduction in the White-tailed Sea Eagle (*Haliaeetus albicilla*) in Sweden. Ambio 2002;31(5):386–405.

Henny CJ, Elliott JE. Toxicology. In: Bird DM, Bildstein KL, editors. Raptor research and management techniques. British Columbia, Canada, Washington, USA: Hancock House Publishers Ltd., Surrey, Hancock House Publishers, Blaine; 2007. p. 329–50.

Hernández M, González LM, Oria J, Sánchez R, Arroyo B. Influence of contamination by organochlorine pesticides and polychlorinated biphenyls on the breeding of the Spanish Imperial Eagle (*Aquila adalberti*). Environ Toxicol Chem 2008;27(2):433–41.

IUCN (International Union for Conservation of Nature)http://www.iucn.org/, .

Jacobson JL, Jacobson SW, Humphrey HEB. Effects of exposure to PCBs and related compounds on growth and activity in children. Neurotoxicol Teratol 1990;12:319–26.

Jaspers VLB, Covaci A, Van den Steen E, Eens M. Is external contamination with organic pollutants important for concentrations measured in bird feathers? Environ Int 2007;33:766–72.

Jaspers VLB, Covaci A, Voorspoels S, Dauwe T, Eens M, Schepens P. Brominated flame retardants and organochlorine pollutants in aquatic and terrestrial predatory birds of Belgium: levels, patterns, tissue distribution and condition factors. Environ Pollut 2006;139:340–52.

Jaspers VLB, Soler-Rodriguez F, Boertmann D, Sonne C, Dietz R, Rasmussen LM, et al. Body feathers as a potential new biomonitoring tool in raptors: a study on organohalogenated contaminants in different feather types and preen oil of West Greenland White-tailed Eagles (*Haliaeetus albicilla*). Environ Int 2011;37:1349–56.

Kenntner N, Krone O, Altenkamp R, Tataruch F. Environmental contaminants in liver and kidney of free-ranging northern goshawks (*Accipiter gentilis*) from three regions of Germany. Arch Environ Contam Toxicol 2003;45:128–35.

Kneubuehl BP. Vergleich der Gefährdung durch abgeprallte bleihaltige und bleifreie Jagdgeschosse. Zentrum Forensische Physik/Ballistik, University BernSwitzerland: Zentrum Forensische Physik/Ballistik, University Bern; 2011 [165 pp. [in German]].

Koskimies P. Birds as a tool in environmental monitoring. Ann Zool Fenn 1989;26: 153–66.

Krone O, Kenntner N, Trinogga A, Nadjafzadeh N, Scholz F, Sulawa J, et al. Lead poisoning in white-tailed sea eagles: causes and approaches to solutions in Germany. In: Watson RT, Fuller M, Pokras A, Hunt WG, editors. Ingestion of lead from spent ammunition: implications for wildlife and humans. Boise,Idaho, USA: The Peregrine Fund; 2009. p. 289–301.

Krone O, Langgemach T, Sömmer P, Kenntner N. Causes of mortality in white-tailed sea eagles from Germany. In: Helander B, Marquiss M, Bowerman W, editors. Sea Eagle 2000. Stockholm, Sweden: Proc. Swedish Soc. For Nat. Conserv./SNF; 2003. p. 211–8.

Lindenmayer DB, Likens GE. Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends Ecol Evol 2009;24(9):482–6.

Lindenmayer DB, Likens GE, Haywood A, Miezis L. Adaptive monitoring in the real world: proof of concept. Trends Ecol Evol 2011;26(12):641–6.

Lutz PM, Wilson TJ, Ireland J, Jones AL, Gorman JS, Gale NL, et al. Elevated immunoglobulin E (IgE) levels in children with exposure to environmental lead. Toxicol 1999;134(1): 63–78.

Mañosa S, Mateo R, Freixa C, Guitart R. Persistent organochlorine contaminants in eggs of Northern goshawk and Eurasian buzzard from northeastern Spain: temporal trends related to changes in the diet. Environ Pollut 2003;12:351–9.

Martínez-López E, Maria-Mojica P, Martínez JE, Calvo JF, Wright J, Shore RF, et al. Organochlorine residues in Booted eagle (*Hieraaetus pennatus*) and Goshawk (*Accipiter gentilis*) eggs from southeastern Spain. Environ Toxicol Chem 2007;26:2373–8.

Martínez-López E, Martínez JE, María-Mojica P, Peñalver J, Pulido M, Calvo JF, et al. Lead in feathers and δ-aminolevulinic acid dehydratase activity in three raptor species from an unpolluted Mediterranean forest (Southeastern Spain). Arch Environ Contam Toxicol 2004;47(2):270–5.

Mateo R, Carrillo J, Guitart R. p,p′-DDE residues in eggs of European kestrel *Falco tinnunculus* from Tenerife, Canary Islands, Spain. Bull Environ Contam Toxicol 2000;65:780–5.

Meyer J, Jaspers VLB, Eens M, de Coen W. The relationship between perfluorinated chemical levels in the feathers and livers of birds from different trophic levels. Sci Total Environ 2009;407:5894–900.

Moore NW, Ratcliffe DA. Chlorinated hydrocarbon residues in the egg of a peregrinefalcon (*Falco peregrinus*) from Perthshire. Bird Study 1962;9(4):242–4.

Movalli P, Duke G, Kessler E. Editorial. Ambio 2008a;37:393.

Movalli P, Lo Valvo M, Pereira MG, Osborn D. Organochlorine pesticides and polychlorinated biphenyl congeners in lanner *Falco biarmicus feldeggii* Schlegel chicks and lanner prey in Sicily, Italy. Ambio 2008b;37:445–51.

Nadjafzadeh M, Hofer H, Krone O. The link between feeding ecology and lead poisoning in White-tailed Eagles. J Wildl Manag 2013;77:48–57.

NFA. Bly I viltkött — riskhanteringsrapport (Lead in game meat — risk management report). National Food AgencySweden: National Food Agency; 2012 [June 2012. 21 + 44 pp. [In Swedish]].

Newton I. The sparrowhawk. T& AD PoyserLondon, UK: T& AD Poyser; 1986.

Newton I, Bogan J. Organochlorine residues, eggshell thinning and hatching success in British sparrowhawks. Nature 1974;249:582–3.

Newton I, Wyllie I, Asher A. Long-term trends in organochlorine and mercury residues in some predatory birds in Britain. Environ Pollut 1993;79:143–51.

NRC (U.S. National Research Council). Animals as sentinels of environmental health hazards. National Academy PressWashington: National Academy Press; 1991.

Pain DJ, Carter I, Sainsbury AW, Shore RF, Eden P, Taggart MA, et al. Lead contamination and associated disease in reintroduced red kites *Milvus milvus* in England. Sci Total Environ 2007;376:116–27.

Pain DJ, Cromie RL, Newth J, Brown MJ, Crutcher E, Hardman P, et al. Potential hazard to human health from exposure to fragments of lead bullets and shot in the tissues of game animals. PLoS ONE 2010;5(4):e10315.

Ratcliffe DA. Changes attributable to pesticides in egg breakage frequency and eggshell thickness in some British birds. J Appl Ecol 1970;7:67–115.

Rattner BA. History of wildlife toxicology. Ecotoxicol 2009;18:773–83.

Riget F, Dietz R, Cleemann M. Evaluation of the Greenland AMAP Programme 1994–1995, by use of power analysis (illustrated by selected heavy metals and POPs). Sci Total Environ 2000;245:249–59.

Roos AM, Bäcklin BM, Helander BO, Rigét FF, Eriksson UC. Improved reproductive success in otters (*Lutra lutra*), grey seals (*Halichoerus grypus*) and sea eagles (*Haliaeetus albicilla*) from Sweden in relation to concentrations of organochlorine contaminants. Environ Pollut 2012;170:268–75.

Scharenberg W, Looft V. Reduction of organochlorine residues in goshawk eggs (*Accipiter gentilis*) from Northern Germany (1971–2002) and increasing eggshell index. Ambio 2004;33:495–8.

Schubert R. Bioindikation in Terrestrischen Ökosystemen. G. Fischer Verlag, Stuttgart. In: Furness RW, Greenwood JJD, editors. Birds as monitors of environmental change. London: Chapman and Hall; 1985. p. 102.

Sergio F, Newton I, Marchesi L. Top predators and biodiversity. Nature 2005;436:192.

Sergio F, Newton I, Marchesi L, Pedrini P. Ecologically justified charisma: preservation of top predators delivers biodiversity conservation. J Appl Ecol 2006;43:1049–55.

Shore RF, Osborn D, Wienburg CL, Sparks TH, Broughton R, Wadsworth R. Potential modifications to the Predatory Bird Monitoring Scheme (PBMS): second report. JNCC Report No. 353. Peterborough, UK: Joint Nature Conservation Committee; 2005. p. 58.

van den Brink NW, Groen NM, De Jonge J, Bosveld ATC. Ecotoxicological suitability of floodplain habitats in The Netherlands for the little owl (*Athene noctua vidalli*). Environ Pollut 2003;122:127–34.

van den Steen E, Pinxten R, Jaspers VLB, Covaci A, Barba E, Carere C, et al. Brominated flame retardants and organochlorines in the European environment using great tit eggs as a biomonitoring tool. Environ Int 2009;35:310–7.

van Drooge B, Mateo R, Vives Í, Cardiel I, Guitart R. Organochlorine residue levels in livers of birds of prey from Spain: inter-species comparison in relation with diet and migratory patterns. Environ Pollut 2008;153:84–91.

van Wyk E, Bouwman H, van der Bank H, Verdoorn GH, Hofmann D. Persistent organochlorine pesticides detected in blood and tissue samples of vultures from different localities in South Africa. Comp Biochem Physiol 2001;129A:243–64.

Vorkamp K, Thomsen M, Møller S, Falk K, Sørensen PB. Persistent organochlorine compounds in peregrine falcon (*Falco peregrinus*) eggs from South Greenland: levels and temporal changes between 1986 and 2003. Environ Int 2009;35:336–41.

Walker CH. Pesticides and birds-mechanisms of selective toxicity. Agric Ecosyst Environ 1983;9:211–26.

Walker LA, Shore RF, Turk A, Pereira MG, Best J. The Predatory Bird Monitoring Scheme: identifying chemical risks to top predators in Britain. Ambio 2008;37:466–71.

Woodruff TJ. Bridging epidemiology and model organisms to increase understanding of endocrine disrupting chemicals and human health effects. J Steroid Biochem Mol Biol 2011;127:108–17.