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An overview of existing raptor contaminant monitoring activities in Europe

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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

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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 subnational 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 ongoing 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
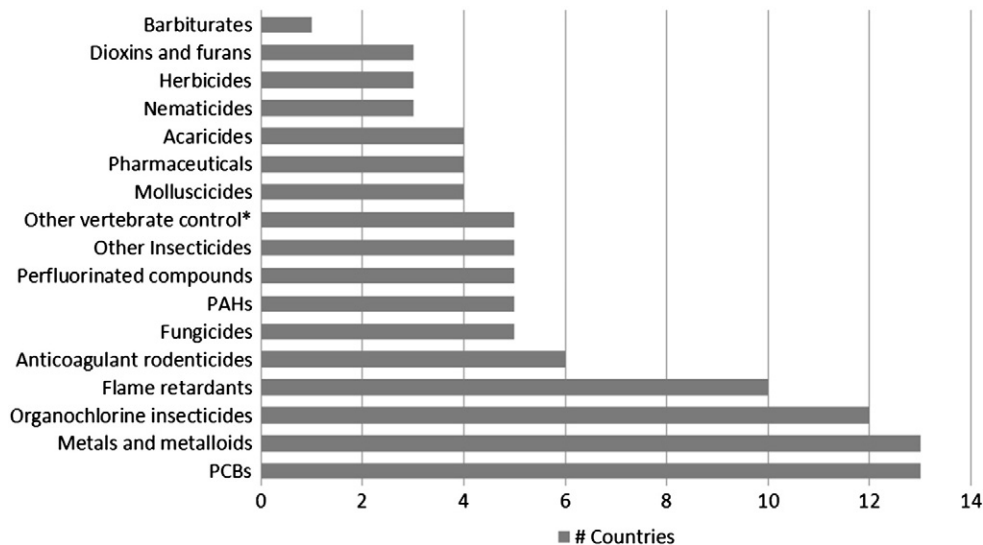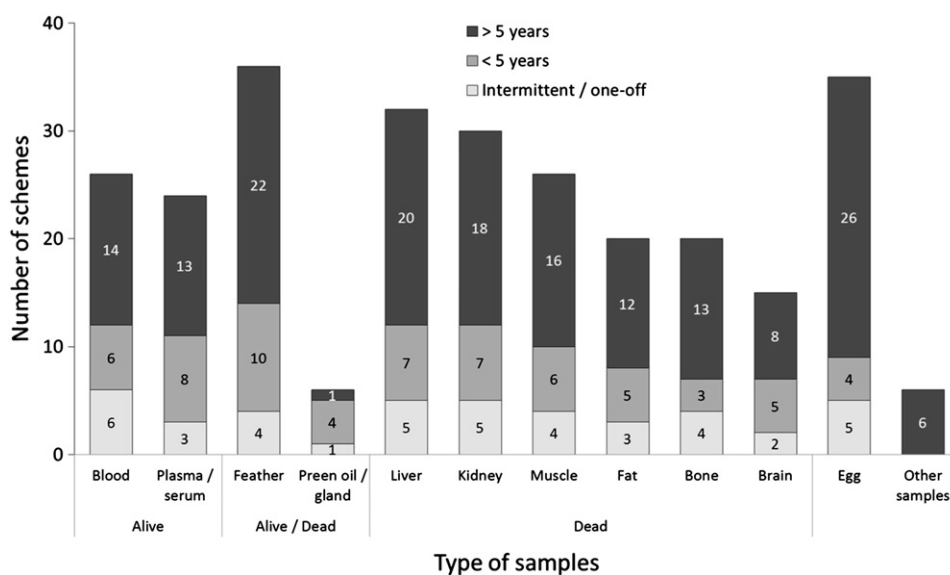

Fig. 2. Number of countries in which monitoring is carried out for different classes of compounds.

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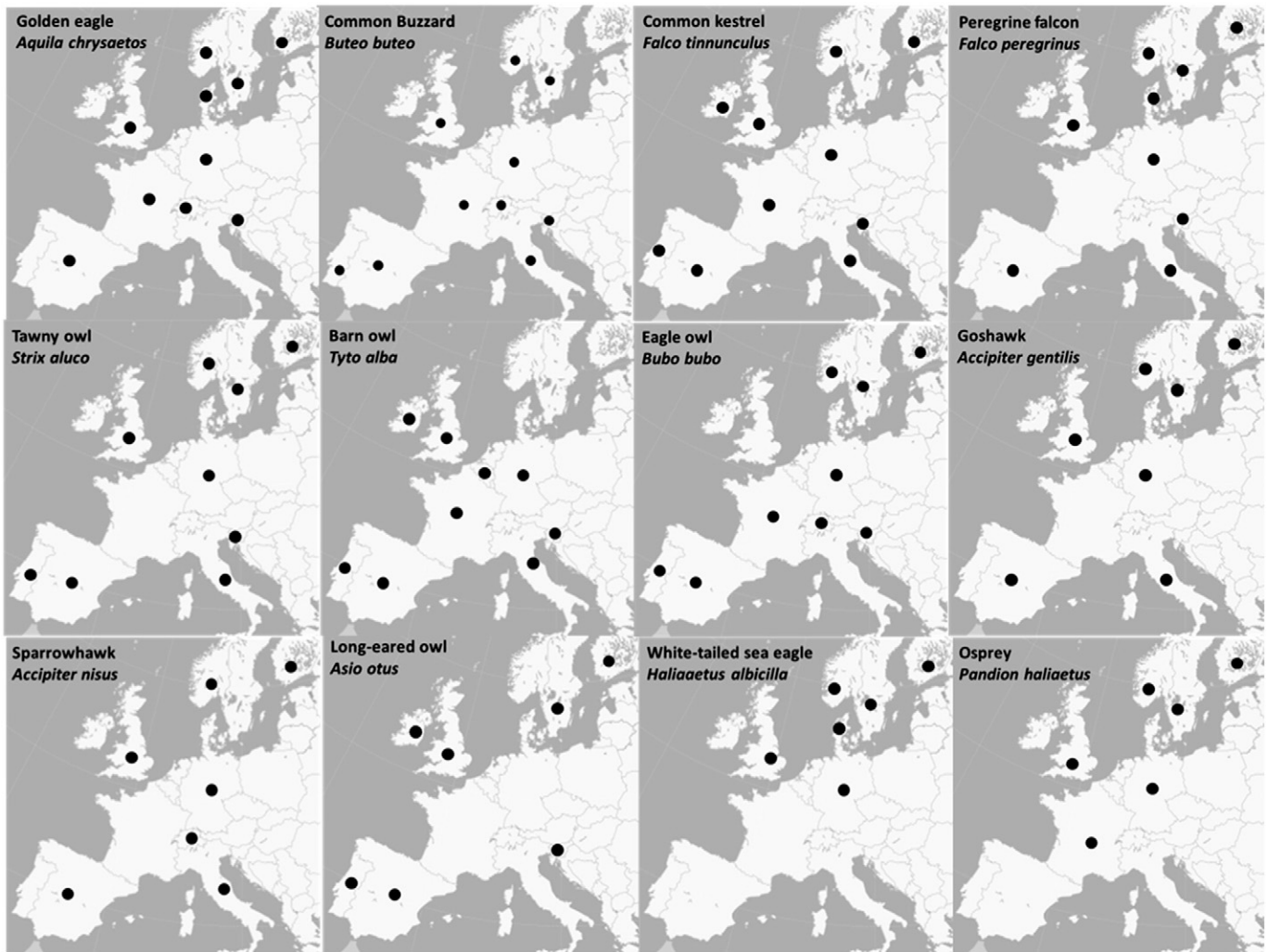
Fig. 4. Maps for the 12 species in which contaminants have been monitored most widely (number of countries) across Europe. Dots indicate countries in which contaminant monitoring has occurred. The position of dots within countries does not indicate the specific location of monitoring.

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
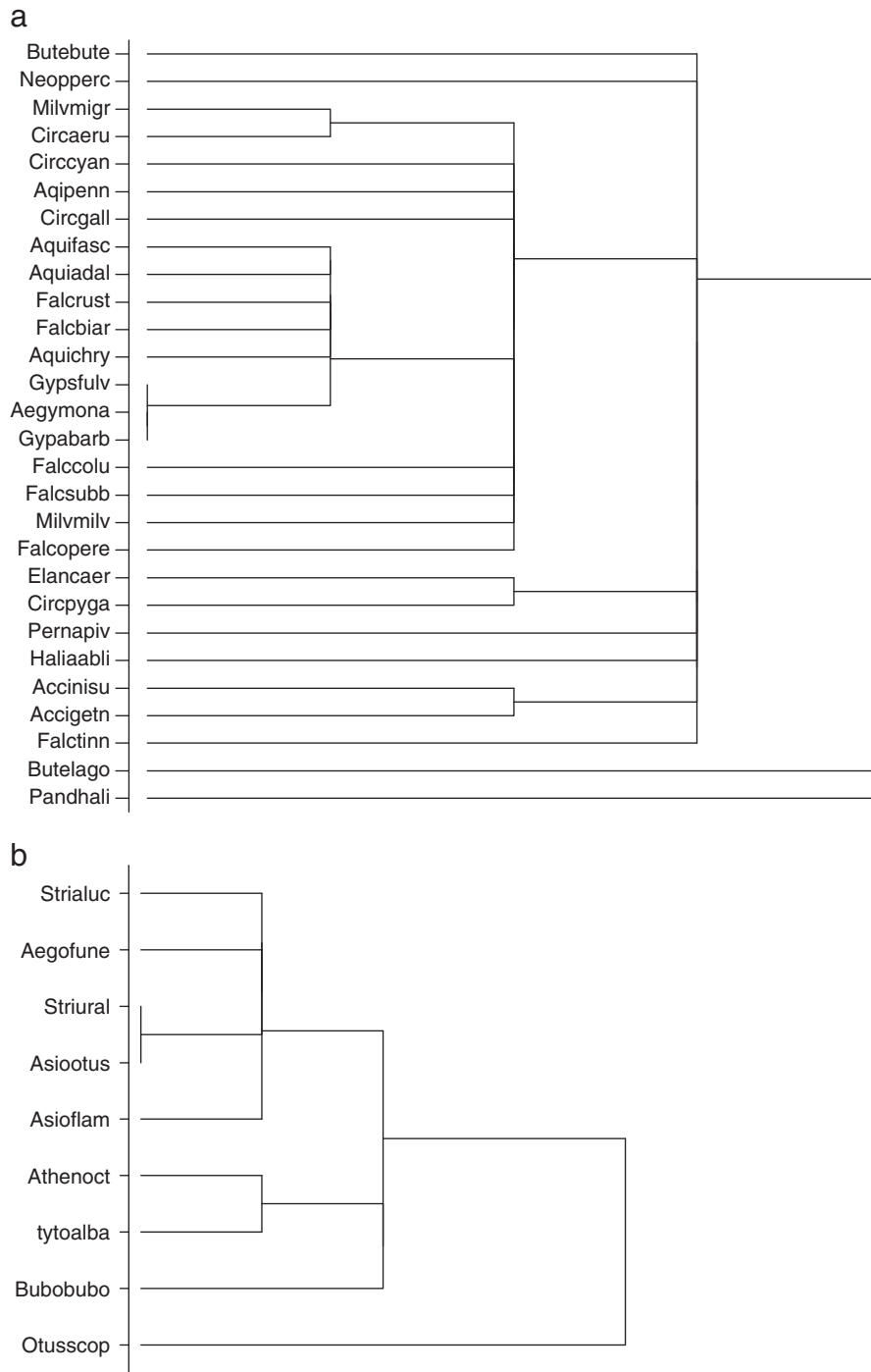
been shown to improve both management practices and strengthening of partnerships between researchers, policy-makers, and resource managers to reconcile policy-relevant and research-relevant goals (Lindenmayer et al., 2011).

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.

a

b

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*).

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