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To cite this article: Paola Movalli, Oliver Krone, Dan Osborn & Deborah Pain (2018) Monitoring contaminants, emerging infectious diseases and environmental change with raptors, and links to human health, *Bird Study*, 65:sup1, S96-S109, DOI: [10.1080/00063657.2018.1506735](https://doi.org/10.1080/00063657.2018.1506735)

To link to this article: <https://doi.org/10.1080/00063657.2018.1506735>



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Published online: 21 Sep 2018.



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Monitoring contaminants, emerging infectious diseases and environmental change with raptors, and links to human health

Paola Movalli^a, Oliver Krone^b, Dan Osborn^c and Deborah Pain^d

^aNaturalis Biodiversity Center, Leiden, Netherlands; ^bDepartment of Wildlife Diseases, Leibniz Institute for Zoo and Wildlife Research, Berlin, Germany; ^cDepartment of Earth Sciences, University College London, London, UK; ^dWildfowl & Wetlands Trust, Slimbridge, UK

ABSTRACT

Capsule: Raptor research and monitoring informs issues of relevance to human health, including environmental contamination, emerging infectious diseases and environmental change.

Aims: The paper examines the relevance of raptor research and monitoring to inform issues of relevance to human health, including environmental contamination, emerging vector-borne diseases and environmental change.

Methods: Reviews of European Union policy context and role of raptor research and monitoring in detection of and response to contaminants. Examples include lead ammunition in White-tailed Sea Eagles *Haliaeetus albicilla* in Europe, and impacts of diclofenac on *Gyps* vultures in the Indian subcontinent. Comments on the relevance of raptor research and monitoring to emerging infectious diseases and environmental change, and considers the links between raptors and humans.

Results: Biomonitoring of contaminants in raptors can perform useful purposes in relation to chemicals legislation. Raptors are useful sentinels of exposure to and effects of chemicals in the environment. Raptor research and monitoring can also elucidate environmental change and spread of emerging infectious diseases. Raptors are linked to humans through social, cultural and economic values.

Conclusion: Raptors can be used to provide information relevant to human health and well-being. There are a number of challenges and opportunities in relating raptor research and monitoring to human health. Several areas with potential for development are outlined. The COST Action 'European Raptor Biomonitoring Facility' and the forthcoming LIFE APEX project will take forward relevant work.

ARTICLE HISTORY

Received 30 June 2017

Accepted 28 June 2018



There is increasing interest worldwide in a 'One Health' approach which links wildlife, environmental and human health (WHO/SCBD 2015). The scope of One Health includes the convergence of environmental health with human, other animal and plant health, and issues such as the detection of and response to contaminants, surveillance and prevention of emerging diseases, and the relationship between environmental change and human health. This paper examines the relevance of raptor research and monitoring to this One Health approach, and how it may usefully inform human health issues, building on a workshop session convened at the EURAPMON Final Conference in Murcia, Spain in 2015 (Vrezec & Bertonecelj 2015).

Following a brief overview of the European Union (EU) policy context, the paper reviews links between raptor research and monitoring and human health and well-being, including in relation to the detection and monitoring of contaminants, emerging infectious diseases and environmental change. The role that

scientific collections of raptor specimens can play in monitoring of contaminants is briefly considered. The paper then addresses two examples in which raptor research and monitoring has been of particular relevance to human health. The first relates to lead ammunition, with a case study on lead intoxication from hunting ammunition in White-tailed Sea Eagles *Haliaeetus albicilla* in Europe. The second relates to the impacts on *Gyps* vultures of the veterinary use of diclofenac in the Indian subcontinent and the repercussions of vulture declines for human health. Finally, consideration is given to the values that link raptors and humans and that help define people's relationships with these animals.

The EU policy context

EU policy or programme activity relevant to research and monitoring of raptors in relation to human health mainly relates to policy and regulation on chemicals,

CONTACT Paola Movalli  paola.movalli@naturalis.nl  Naturalis Biodiversity Center, Darwinweg 2, 2333 CR Leiden, Netherlands

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and also includes the programme on emerging and vector-borne diseases and policy on environmental change.

There is growing concern in the EU and worldwide about negative human health and environmental impacts associated with various chemicals. A wide range of legislation has been put in place to reduce these impacts. This includes legislation on industrial chemicals (REACH – EC 2006), Biocides (EC 2012), Plant Protection Products (EC 2009) and Medical and Veterinary Products (EC 2004). The Water Framework Directive (EC 2000) and Marine Strategy Framework Directive (EC 2008) seek to establish good ecological/environmental status, including in relation to chemical contaminants. The European Community is also a party to relevant international conventions including the Minamata Convention (UN 2013) on mercury, the Stockholm Convention on persistent organic pollutants (UN 2001) and the Helsinki Convention (HELCOM 2014) and Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR 2007) relating to the quality of the marine environment.

However, considerable scientific concern remains that current actions to safeguard environmental and human health from the impacts of toxic chemicals are insufficient and there are important parallels between the increasing incidence of human disorders and those observed in wildlife (Bergman *et al.* 2013). Moreover, the environmental fates of only a few of the estimated 70 000 chemicals commonly used in industry have so far been characterized (Koizumi *et al.* 2009).

Biomonitoring of contaminants in raptors is of particular relevance to much of this legislation, including: (a) for environmental hazard assessment, triggering of substance evaluation (in a ‘weight-of-evidence’ approach), early warning of bioaccumulation problems and triggering of more rigorous assessments of persistent, bioaccumulative and toxic (PBT) and very persistent and very bioaccumulative chemical assessments under the EU REACH regulation; (b) for substance assessment, development of guidance in relation to exposure and bioaccumulation, and post-market vigilance under the EU plant protection products and biocides regulations; (c) to demonstrate if the outcomes of the convention translate into a reduction in mercury contamination in environmental sentinel species, under Article 19 of the Minamata Convention; (d) for post-market vigilance under the EU medicinal and veterinary products regulation; (e) to provide exposure data for priority substances in top predators to provide a reality-check for calculated (theoretical) exposure values under the EU Water Framework Directive and Marine Strategy Framework

Directive; (f) for assessment of the quality of the marine environment (e.g. in terms of implementation of the Hazardous Substances Strategy, monitoring programmes including raptors such as the White-tailed Sea Eagle) under the Helsinki and OSPAR Conventions.

Regarding emerging vector-borne diseases, the European Centre for Disease Control runs a major programme aimed at monitoring their spread and limiting their health impacts (Semenza & Zeller 2013).

Regarding environmental change and human health, there is increasing recognition of the potential health impacts of environmental change including change resulting from climate change and biodiversity loss (e.g. ASC 2016). Environment and health are broadly addressed by the EU’s 7th Environment Action Programme (EU 2013). An earlier Environment and Health Strategy (EC 2003) and Action Plan 2004–10 (EC 2004) are largely obsolete and in need of updating.

Links between raptor research and monitoring and human health

Detection of and response to contaminants

While other animals can be useful sentinels of environmental contamination (Newton *et al.* 1993, Rattner 2009), raptors (birds of prey, owls and scavengers) are especially suitable for monitoring PBT chemicals (Sergio *et al.* 2005, 2006) because they are typically relatively long-lived apex predators. It has been suggested that they may also effectively integrate contaminant exposure both over time (Furness 1993) and relatively large spatial areas, they are relatively easily studied and captured (especially nestlings) which facilitates collection of samples (e.g. blood, feather, preen gland oil) without sacrificing animals, and their populations can be monitored and quantified. Sampling can often be scheduled during regular ringing programmes to minimize any additional stress (Espín *et al.* 2016). These are all criteria identified by the US National Research Council as requirements for sentinel species (NRC 1991). In summary, raptors can provide a window into the overall functioning of the environment (Movalli *et al.* 2008).

Well-known examples of the detection of contaminants in raptors and other higher trophic level bird species, some of which have resulted in impacts on individuals and populations and management responses by governments, include eggshell thinning in raptors (organochlorines; Ratcliffe 1970, Fernie *et al.* 2009); polychlorinated biphenyls (PCBs), organochlorines and methyl mercury in some fish-

eating birds at levels known to cause effects on breeding and on the immune system (Hickey & Anderson 1968); and haemorrhage and death of protected non-target species (anticoagulant rodenticides) (Walker *et al.* 2008). Government actions to reduce exposures, while limited, have proven to be effective in specific cases (e.g. bans and restrictions on lead, chlorpyrifos, tributyltin, PCBs and some other persistent organic pollutants as illustrated by Newton & Wyllie 1992). This has contributed to decreases in the frequency of disorders in humans and wildlife (Bergman *et al.* 2013).

Like humans, raptors can experience acute and chronic health impacts following exposure to pollution in air (Olsgard *et al.* 2008, Sanderfoot 2017), water or food (Movalli *et al.* 2017a). Raptor-based sentinel systems can expedite recognition of dangerous environmental conditions, illustrate pollutant bioavailability and highlight health hazards associated with known contaminants, providing an approximation of what people might experience (Backer & Miller 2016). Some raptors can also deliver key ecosystem services, such as the consumption of carrion by vultures, the loss of which can have a negative impact on human health (Markandya *et al.* 2008).

Little is known about which compounds occur in the predominant mixtures in the environment. Research and monitoring of contaminants in raptors may help elucidate spatial patterns of real life exposure to such mixtures (Newton *et al.* 1992, Broughton *et al.* 2003) and, importantly, help further our understanding of their effects on humans and wildlife (Bergman *et al.* 2013).

In recent years, a growing body of scientific research suggests substances in the environment may interfere with the function of the endocrine system of humans and wildlife (Bergman *et al.* 2013). Endocrine disrupting chemicals (EDCs) may produce a wide spectrum of adverse effects on both human health and wildlife (Scognamiglio *et al.* 2016). Exposure data (and ultimately data on effects) in wildlife can help in the interpretation of data on human exposure and effects.

A well-known example of subtle effects on raptors is eggshell thinning and associated decreased breeding productivity in many raptor species associated with dichlorodiphenyldichloroethylene exposure (Peakall 1993, Felton *et al.* 2015). This classic example illustrates that the unknown or unintended by-products that are formed during chemical manufacturing, during combustion processes and via environmental transformations add greatly to the number of chemicals in our environment and the complexity of evaluating their impacts (Bergman *et al.* 2013).

The increase in non-communicable diseases in humans and wildlife over the past 40 years indicates an important role of the environment in disease aetiology. Human and wildlife studies, in the absence of experimentation, cannot establish cause and effect, but can reveal associations between exposure to EDCs and human health effects. For instance, by looking at multiple EDCs, one can explore whether additive effects correlate to the incidence of health effects in humans (Bergman *et al.* 2012). Studies of exposed wildlife provide important information on exposure levels, early and subclinical effects and the clinical neurotoxicity of EDCs, because the mechanisms underlying effects and outcomes of exposure are often similar to those in humans. Such research can lead to primary prevention measures, delivering significant social and economic benefits. A clear example of the success of primary prevention through exposure control is lead, which was widely prohibited as an additive to car fuels, with rapid benefits to public health (Martínez *et al.* 2013).

Emerging vector-borne diseases and other infections

Our understanding of the interactions between ecosystem change, disease regulation and human well-being is in its infancy. Holistic, 'One Health' approaches to the management and mitigation of the risks of emerging infectious diseases have the greatest chance of success (Cunningham *et al.* 2017). An example of this relates to detection and monitoring of the spread of a recently emerged viral zoonosis, the West Nile Virus (WNV), in Europe and the USA. WNV is an arthropod borne flavivirus, related to Japanese encephalitis virus and St. Louis encephalitis virus, and is potentially fatal in humans (Hernández-Triana *et al.* 2014). It is transmitted within its natural (sylvatic) cycle by *Culex* mosquitoes and other arthropods (Komar 2000). Recent outbreaks of human disease in Algeria, Central Europe and Russia are thought to be related to migration of infected birds. Birds are the natural reservoir of the virus, and migratory birds may be playing an important role in introduction or re-introduction of the virus in some areas. The majority of WNV transmission between birds occurs through mosquito bites. However, transmission through faeces (Kipp *et al.* 2006) as well as oral transmission should not be discounted and suggestions for this route of transmission have been found in birds of prey in Spain, Hungary, Israel and North America (Wodak *et al.* 2011). Raptors in Europe and the USA are increasingly affected by WNV.

For example, Erdélyi *et al.* 2007 found a specific genetic lineage (Lineage 2) of WNV in European raptors. Goshawks *Accipiter gentilis* and European Sparrowhawks *Accipiter nisus* appeared highly susceptible to this lineage of WNV. These findings and those of others (Bakonyi *et al.* 2006) suggest that different WNV strains circulate simultaneously in Europe. Work on the spread of WNV in raptors, for example in Austria, is already providing information on the potential risks to humans (Ziegler *et al.* 2013, Bakonyi *et al.* 2013).

Raptors have also been found to show infection with candida strains resistant to antifungal therapies. Monitoring of candida in the gastrointestinal tract of raptors may therefore help elucidate risks to human health from the environmental presence of contaminants that lead to resistant strains of candida (Brilhante *et al.* 2012).

Raptors can similarly be used to explore exposure to antibiotics, antibiotic-resistant genes and multi-drug-resistant microbes (Jurado-Tarifa *et al.* 2016). Antibiotic-rich effluents have been shown to promote the development of antibiotic-resistant microbes in the environment. Any role that wildlife may play in the transfer of antibiotic-resistant microbes between humans and the environment is of concern and merits investigation (Shore *et al.* 2014).

Free-ranging animals harbour a wide variety of ecto- and endoparasites and birds of prey may host endoparasites with complex life-cycles. For example, trematodes usually have a heteroxenous development cycle involving one or more intermediate hosts before finally reaching the definitive (raptor) host where the parasite matures and reproduces. Birds of prey involved in complex parasite life-cycles may therefore act as sentinels for the integrity of the food web (Krone & Streich 2000).

Environmental change

Many interacting factors contribute to environmental change (Millennium Ecosystem Assessment 2005) and evaluating the role that raptors can play in monitoring such change is challenging. New research techniques are needed to make progress here and investigate links with human health. Stable isotope analysis of raptor tissues, in particular of carbon ($\delta_{13}\text{C}$) and nitrogen ($\delta_{15}\text{N}$), is a proven technique that can reveal temporal or spatial changes in feeding ecology and in habitat use and migration pathways (Lott & Smith 2006, Catry *et al.* 2016). Environmental changes, contamination and emerging diseases are frequently linked. For example, the emergence of infectious diseases is

frequently influenced by anthropogenic environmental change (Daszak *et al.* 2001). For example, the establishment and maintenance of vector populations and the associated threat of vector-borne pathogen transmission in northern latitudes may be facilitated by global environmental change (Smith *et al.* 2018). Raptor research and monitoring may offer potential to explore these linkages.

The role of scientific collections

Museum collections have considerable potential value in taking forward the One Health agenda and specifically in providing large collections of raptor specimens for research linked to environmental and human health. Regarding environmental contaminants, the link between chlorinated hydrocarbons in DDT (dichlorodiphenyltrichloroethane) and the decline of the Peregrine Falcon *Falco peregrinus* was revealed by studies on museum collections of raptor eggs (Ratcliffe 1967, Hickey & Anderson 1968, Peakall *et al.* 1976, Peakall & Kiff 1979). This helped raise awareness of the potential risks to humans.

While contaminant studies generally use tissues and organs not normally preserved by museums, such as muscle and liver, such tissues may sometimes be available. For example, small amounts of muscle tissue now preserved by museums for genetics research may prove valuable for contaminant research (Rocque & Winker 2005). Further, many museums receive contemporary raptor specimens that, if treated and stored following appropriate protocols, can yield samples appropriate for contaminant studies. Such specimens are potentially amenable to both targeted analysis of substances of concern, as well as non-target screening for detection on emerging contaminants and predominant mixtures in the environment.

Historical collections of raptor samples (e.g. feathers, eggs, blood, muscle, kidney, adipose tissue, bone) from museums and environmental specimen banks (ESBs) offer the potential to research contaminant levels in raptors over space and time, allowing better-informed interpretation of modern-day contaminant levels (Movalli *et al.* 2017b), though elucidation of effects is more challenging. ESBs generally apply stricter protocols than museums for sample collection, treatment and storage in view of subsequent contaminant analysis. This should be taken in to account when using museum specimens. In future, museums receiving new samples could seek to adopt ESB protocols to enhance the value of their samples for contaminant research.

Feathers from birds in museum collections offer great potential for the study of synoptic geographical and

historical changes in mercury levels on a global scale with large sample sizes (Monteiro & Furness 1995). Feathers from collections can also be useful for retrospective biomonitoring of persistent organic pollutants, as has successfully been done for heavy metals (Burger 1993) and to study regional and temporal trends (Rocque & Winker 2005, Behrooz *et al.* 2009).

Regarding environmental change, museum collections can be used for work to elucidate historical change in habitats, and this can inform thinking on the likely impacts on such change on human health and well-being (Inger & Bearhop 2008, Lister *et al.* 2011).

At Naturalis, a pilot project has been carried out to demonstrate the potential to exploit the extensive collection of raptor specimens to derive data on historical levels of persistent, bioaccumulative and toxic chemicals. This work involved the analysis of feathers from collections of Common Kestrel *Falco tinnunculus*, using neutron activation at the instrumental neutron activation analysis facility at Delft University of Technology for over 50 metals and other elements. Some samples showed mass fractions of certain elements (chromium, cadmium, selenium, arsenic) above levels known to have adverse effects (Movalli *et al.* 2017a).

Risks to raptors and humans from exposure to lead from ammunition

Lead is a good example of a One Health issue. It is a highly toxic non-essential heavy metal with no biological function and it negatively affects many body systems. Lead compounds are classified by the International Agency for Research on Cancer as possible carcinogens (IARC 2012). Lead is an endocrine disruptor with reproductive effects in both men and women (Telisman *et al.* 2000). Lead differs from many contaminants in that there is no evidence for a threshold for a number of critical endpoints including developmental neurotoxicity and nephrotoxicity, that is, it has not proven possible to determine a level below which observable effects in humans cannot be seen (EFSA 2010). Lead affects all animals in which it has been studied, from migratory birds to humans. Lead from ammunition presents risks to wildlife – especially wild birds (Watson *et al.* 2009, Pain *et al.* 2015), to domestic stock (Payne *et al.* 2013) and to humans (Green & Pain 2015).

Natural sources of lead exist, but it is the widespread use of lead by humans that has dispersed it around the globe and substantially increased exposure. Lead has been widely mined and smelted and its uses have

included as an additive to paints and petrol, as a material for making domestic water pipes, in batteries, to produce weights for anglers and ammunition. As evidence of the impacts of chronic low level lead exposure on human health, especially neurodevelopment in children, has accumulated over decades, most uses of lead have been heavily regulated or banned. Lead-based ammunition is considered to be the most significant unregulated source of lead deliberately emitted into the environment in the EU (Group of Scientists 2014).

Very large numbers of game animals are shot annually in the EU (tens of millions in the UK alone; Green & Pain 2015) using lead ammunition and an unknown proportion are unrecovered. In some places viscera from shot large game animals (e.g. ‘gralloch’ from deer) are often discarded in the countryside before the carcass is retrieved. In addition, many game animals (e.g. averaging 20–25% for investigated wildfowl populations from numerous studies globally; Pain *et al.* 2015) survive being shot but are wounded and carry fragments of lead ammunition. Dead and un-retrieved animals and wounded but living animals shot with lead ammunition are available as an easy source of food for scavenging and predatory raptors. Both lead bullets and shotgun pellets fragment on passage through the shot animal, often leaving tiny pieces of lead which can be distant from the wound channel (reviewed in Gremse *et al.* 2014, Pain *et al.* 2015); feeding raptors can then ingest this lead.

The likelihood that raptors will be exposed to lead from ammunition depends upon their propensity to consume game species, to scavenge, the time of year (open or closed hunting season; Elliott 1992, Pain *et al.* 1997) and hunting intensity in their foraging range (Wayland & Bollinger 1999). Exposure to shot is higher during the hunting season as measured by the incidence of shot found in regurgitated raptor pellets (Helander 1983, Pain *et al.* 1997, Mateo *et al.* 2013). Poisoning from ingested lead is usually confirmed through the analysis of lead in tissues such as blood, liver or kidney, where again there are spatial and temporal relationships related to hunting (Green *et al.* 2008, Kelly & Johnson 2011) and some authors have confirmed the origin of the lead using stable isotope analysis (Pain *et al.* 2007, Finkelstein *et al.* 2012).

Lead poisoning is a significant cause of mortality in many raptor species in the EU and elsewhere in the world. For example, it is responsible for over 20% of reported causes of mortality of White-tailed Sea Eagles in some parts of Europe (Kenntner *et al.* 2001, Krone *et al.* 2006) and a key factor in the decline of the Critically Endangered California Condor *Gymnogyps*

californianus. For the latter species, there would have been no population recovery without action to address this threat (Meretsky *et al.* 2000, Green *et al.* 2008, Finkelstein *et al.* 2012). Species in Europe particularly vulnerable to the ingestion of lead fragments from ammunition in their prey include the Golden Eagle *Aquila chrysaetos* (Kenntner *et al.* 2007), White-tailed Sea Eagle (Krone *et al.* 2006, Helander *et al.* 2009), Eurasian Griffon Vulture *Gyps fulvus* (Berny *et al.* 2015), Marsh Harrier *Circus aeruginosus* (Pain *et al.* 1997), Bearded Vulture *Gypaetus barbatus* and Egyptian Vulture *Neophron percnopterus* (Donazar *et al.* 2002), all of which are EU Birds Directive Annex I listed species, with the latter two also being near threatened and globally threatened (Endangered) respectively (BirdLife International 2018).

The route of exposure of humans to lead from ammunition is similar to that of raptors, i.e. primarily the consumption of lead fragments from ammunition in the flesh of game animals (Dobrowolska & Melosik 2008, Knott *et al.* 2010, Pain *et al.* 2010). In the EU, Commission Regulation 1881/2006 sets maximum levels for certain contaminants in food; for lead the maximum level is 0.1 ppm in bovine animals, sheep, pigs and poultry (excluding offal). No minimum level has been set for game meat, in which average levels in the UK (gamebirds) and EU (all game) can exceed the EU minimum level for domestic animal meat by 12–31 times respectively (Pain *et al.* 2010, EFSA 2010). Lead affects humans in a similar way to other animals with highest risks to the nervous system, especially the developing brain in babies and young children. The number of children that might be affected by a 1 point (1%) reduced IQ (intelligent quotient) in the UK as a result of eating game shot with lead has been estimated to be probably in the range of 4000–48 000 (Green & Pain 2015). National food safety and risk assessment agencies of five European (four EU) countries have evaluated risks and advised that pregnant women, babies and young children avoid eating game meat shot with lead ammunition or reduce the amounts consumed (summarized in Knutsen *et al.* 2015).

Raptors and humans share similar exposure routes to lead from ammunition and their biological systems are affected in broadly similar ways. Lead poisoning from ammunition sources in raptors was recognized before the risks to humans from this source were understood, partly because little was known about the degree of fragmentation of lead ammunition until the last few decades. Raptors have proven good sentinels here, and may do so with other toxic chemicals. Exposure of susceptible raptors across the EU will to some extent parallel human exposure and the monitoring of lead

poisoning in raptors over time will give an indication of changes in this risk.

Case study: lead poisoning in White-tailed Sea Eagles in Europe

The oral ingestion of lead-based bullet fragments and lead shot embedded in live prey, carrion or viscera left behind by hunters poses the most important mortality factor for the White-tailed Sea Eagle accounting for 25% of the mortality in Germany (Kenntner *et al.* 2001, Krone *et al.* 2009). Lead poisoning in White-tailed Sea Eagles has been diagnosed in Sweden (Helander *et al.* 2009), Finland (Krone *et al.* 2006), Poland (Falandysz *et al.* 1988), but also outside of Europe in Japan (Kim *et al.* 1999) and Greenland (Krone *et al.* 2004).

To investigate lead poisoning in the White-tailed Sea Eagle, as an umbrella species for other scavenging birds, and to develop potential solutions to the problem, the Leibniz-Institute for Zoo and Wildlife Research with funding from the Federal Ministry of Education and Research carried out research on home range size, food choice and feeding behaviour of the White-tailed Sea Eagle and on the performance of lead-free compared to lead-based ammunition.

At 2.25–19.16 km², the relatively small home range of White-tailed Sea Eagles (Krone *et al.* 2013) illustrates the importance of local food choice in influencing exposure to lead in Germany (Nadjafzadeh *et al.* 2013) and suggests that regional hunting activities are responsible for the lead uptake from spent ammunition. Selective feeding enables eagles to avoid large metallic particles. This is relevant for the ammunition industry in the development of lead-free rifle bullets, which ideally fragment into a few large particles or, even better, are purely deforming projectiles (Nadjafzadeh *et al.* 2015). These lead-free bullets have been shown to perform as effectively as lead-based bullets (Trinogga *et al.* 2013).

Discourse and conflict analyses were conducted to better understand the arguments and concerns of different stakeholders. A national questionnaire examined hunters' level of understanding of the issue. Results indicated that hunters were generally aware both of the issues and that the use of lead-free bullets could reduce lead poisoning in eagles. Results suggested that should lead-free bullets perform as well as lead-based bullets most hunters would switch to lead-free ammunition.

Follow-up studies were carried out on safety aspects of rifle bullets, on the performance of lead-free bullets under real hunting conditions and on the relationship between contamination of game meat with lead

fragments and consumers' health. The safety aspects studied revealed no significant differences in the ricocheting or rebound behaviour of lead-based and lead-free bullets (DEVA *et al.* 2011, Kneubuehl 2011). Bullet performance was tested under real hunting conditions by comparing flight distances of game animals shot. These did not vary between animals shot with lead-based or lead-free projectiles with equal terminal ballistic performance parameters (Gremse & Rieger 2012). Game meat hygiene and consumer risk in the context of lead-based ammunition has been studied by the German Federal Institute for Risk Assessment (Bundesinstitut für Risikobewertung, BfR). The BfR recommended that children up to 7 years, pregnant or fertile women should relinquish game meat harvested with lead-based bullets. Furthermore, people who frequently consume game meat should avoid eating parts of the game animal near the wound canal and switch between game species, since this is likely to reduce lead uptake. The BfR also indicates that the use of alternative lead-free ammunition significantly reduces lead deposition in the animals' tissue (BfR 2014).

While a discussion is beyond the scope of this paper, the importance of ensuring appropriate testing of the relative safety of alternative materials to replace lead in ammunition, as already required for gunshot in the USA (where there is a mandatory approval process for nontoxic shot types and shot coatings; USGPO 2014), should be noted (Thomas *et al.* 2015, Thomas 2016).

Links between the use of diclofenac in livestock and raptor and human health

Vultures of the *Gyps* genus (Oriental White-backed *Gyps bengalensis*, Long-billed *Gyps indicus*, Slender-billed *Gyps tenuirostris*) were once widespread and common across the Indian subcontinent, in total numbering in the millions. *Gyps* vultures are obligate scavengers feeding primarily on the carcasses of dead ungulates, and their high densities resulted from a superabundance of dead livestock. Cows are considered to be sacred in India, and allowed to die naturally in the wild, after which they are skinned for the leather industry and vultures then eat the flesh, picking the bones clean. However, vulture populations underwent a rapid decline, and surveys found that Oriental White-backed Vultures declined by over 99% and the other two species by 97% between 1992 and 2007 in India (Prakash *et al.* 2007). These rapid declines were mirrored in neighbouring Pakistan and Nepal (Gilbert *et al.* 2002, Watson *et al.* 2004).

Several groups of researchers investigated the causes of these dramatic declines. An obvious first contender was a contaminant of the food supply as vultures feed communally; however, other scavengers appeared unaffected and toxicological testing of dead livestock for obvious contaminants proved negative. The declines appeared to be only in the *Gyps* genus and to spread radially from within India to surrounding countries. This, along with the lack of an obvious contaminant source, initially suggested that an infectious agent might be responsible, and histopathological findings were consistent with the cause being a possible viral infection (Cunningham *et al.* 2003). Most dead birds were found at post mortem to have visceral gout, i.e. an accumulation of uric acid crystals on their tissues. A breakthrough came when Lindsay Oaks working in Pakistan looked at possible causes of visceral gout and discovered that a non-steroidal anti-inflammatory drug (NSAID), the painkiller diclofenac, had been introduced to treat livestock at about the time the vultures started to decline. NSAIDs can sometimes be associated with kidney problems that could lead to visceral gout. Subsequent research in Pakistan and India showed diclofenac to be the cause of the declines across the subcontinent (Green *et al.* 2004, Oaks *et al.* 2004, Shultz *et al.* 2004). As a cheap and effective painkiller and anti-inflammatory drug, many livestock were being given diclofenac as a welfare drug in the final stages of life. Any cattle that died shortly afterwards and containing sufficiently high quantities of diclofenac proved fatal to feeding *Gyps* vultures, which were found to be highly sensitive to the drug.

A short period of intensive research resulted in the identification of meloxicam as an alternative, effective and out of patent NSAID, safe for *Gyps* vultures and many other scavenging birds (Swarup *et al.* 2007). Subsequently, the governments of India, Pakistan and Nepal took rapid action to ban the manufacture and sale of veterinary diclofenac. While there is much to be done to recover vulture populations to even a fraction of their previous numbers, the rapid declines seen until a decade ago appear to have been stemmed and there are the first indications of the low populations stabilizing and perhaps even beginning to increase in one species (Prakash *et al.* 2012).

In an environmental economics paper Markandya and colleagues (2008) estimated the potential cost to Indian society of the dramatic declines in vultures. This was based on estimating the amount of dead livestock tissue that would have become available following the vulture declines and the number of feral dogs, the other main scavenger of ungulate carcasses

that this additional food could support. The incidence of human rabies in India is relatively high and human rabies cases frequently result from feral dog bites. The authors estimated the number of additional dog bites and subsequent potential morbidity and mortality from human rabies that could occur over a 15-year period due to an increase in the number of feral dogs. This estimate was about 48 000 additional deaths from human rabies, with an estimated total health cost to the Indian economy of 34 billion dollars over 14 years. This gives a stark illustration of a link between the population trends of *Gyps* vultures and human health.

Gyps vultures are extremely sensitive to diclofenac. While they have not acted as sentinels for direct effects in humans in the manner that raptors and other birds have acted as sentinels for lead contamination, they have nonetheless acted as sentinels of indirect effects on humans through the estimated increasing incidence of rabies. Moreover, the discovery of the effects of diclofenac in *Gyps* vultures (alongside other work) has helped raise concern regarding diclofenac in other contexts (e.g. potential toxicity to fish, Schwarz *et al.* 2017). Diclofenac is one of only a few pharmaceuticals shown to have provoked direct toxicological effects in wildlife – another being the presence in water bodies of synthetic oestrogen 17 α -ethinyloestradiol, a common ingredient in the human contraceptive pill (Shore *et al.* 2014), which causes the feminization of male fish (Kidd *et al.* 2007, Caldwell *et al.* 2008). Diclofenac is one of only two such substances on a Watchlist under the EU Water Framework Directive (Tavazzi *et al.* 2014).

It is notable that diclofenac is likely not the only NSAID that puts vultures at risk, with others such as flunixin, nimesulide and ketoprofen having been implicated (Cuthbert *et al.* 2007, 2011, 2016, Taggart *et al.* 2009, Fourie *et al.* 2015, Zorrilla *et al.* 2015). Appropriate testing and a high level of vigilance are needed with the veterinary use of any NSAIDs that have not been shown to be safe to scavengers, and that could become available to them. It is also suspected that diclofenac may be toxic to certain other avian scavengers; two dead Steppe Eagles *Aquila nipalensis* were found at a carcass dump in India in 2012, both with visceral gout and one with concentrations of diclofenac similar to those found in the tissues of dead vultures (Cuthbert *et al.* 2016). This opens up the possibility that diclofenac may be toxic to other *Aquila* eagles, including the Golden Eagle *A. chrysaetos*.

In the EU, both Spain and Italy have licensed the sale of veterinary diclofenac, despite the fact that the Iberian Peninsula, France and Italy include the bulk of the European vulture populations. This presents a key risk to vultures and campaigns are underway to ban the

veterinary use of diclofenac in an attempt to avoid the catastrophic declines seen across the Indian subcontinent. Both the current sale of diclofenac in these European countries, and the knowledge that certain other NSAIDs may also be toxic to vultures, highlight the need for a comprehensive raptor monitoring programme across Europe. This should involve the systematic recording in dead raptors (and other livestock scavengers) at post mortem of the presence or absence of visceral gout, with collection of tissues for NSAID screening when this is found.

Both the lead ammunition and NSAID case studies show the value of a One Health approach to the investigation, prevention and management of risks from contaminants in both raptor populations and human society.

Valuing links between people and raptors

As well as the disease and toxicological One Health links between raptors and human health and well-being, evidence is needed on social, cultural and economic (and even, in the past at least, military or political) links if an effective One Health policy perspective is to be formulated and implemented. These complex links need to form part of the policy evidence base because, as they play out at local scales, the societal significance of toxicological risks can be amplified and societal damage costs can increase (as in the case of the impact of NSAID veterinary products on vultures in India) or there might be increased vulnerability to biosecurity or conservation risks (e.g. through the capture and movement of birds for trade).

There has been relatively little research on these aspects of raptors and human health and well-being, even though, to use a historical example, it is thought that expertise in falconry helped feed the armies of Genghis Khan (MaMing *et al.* 2014) and raptors are national emblems for many modern nations (e.g. the USA, Germany, Poland). They are also important to business sectors such as tourism. The practice of using falconry to hunt game for human food is extant in central Asia (MaMing *et al.* 2014).

Some studies have focused on the economic value of raptors. Dickie *et al.* (2006) estimate a contribution to the local economy of over £1 million per annum for one Osprey site alone; at about the same time, wildlife watching in the whole of Scotland was valued at about £140 million with tourism as a whole being valued at almost £1.6 billion. Molloy (2011) showed that of the £58 million spent by visitors to Mull (Scotland) up to 10% of this was attributable to the population of White-tailed Sea Eagles, and that these birds were of

themselves the 6th most important reason people gave for visiting Mull.

Economic values are not however the only value that needs to be accounted for. When Bruns (1960) made an early attempt to establish a rigorous way of assessing the economic value of birds to forestry as a means of enhancing an approach to conservation that would balance the needs of birds and people it appears the cultural and social factors were set aside. More modern approaches seek to recognize and include these factors (UK NEA 2011, Albon *et al.* 2014, Mace 2014, UNEP/WHO 2015). It seems the importance of cultural and social factors linked to raptors has yet to be described in the academic literature in clear cut terms other than in parts of Asia, despite the importance these factors can have in creating public and political opinion on raptor conservation issues (such as EU bans on harmful chemicals such as the organochlorines). If seemingly perverse regulatory decisions are not to be made – such as allowing known raptor poisons to be introduced into the EU – then such values must be better understood.

Conclusion

This paper has outlined the ways in which raptor research and monitoring can make a useful and varied contribution to the One Health agenda. Links have been drawn not only between exposure to contaminants and their impacts on raptors but also to the broader effects these links can have on human society. These wider impacts can have consequences for human well-being as well as human health. This suggests raptors could be used to provide information relevant to human health and well-being and that raptor studies have a role to play in identifying when environmental changes are underway that might require action to be taken by people at a number of governance levels (this could mean action by governments, businesses or individuals and their communities). This is because, as top predators, they integrate information about both their environment and the people's, and store this record in their tissues.

There are a number of challenges and opportunities in relating raptor research and monitoring to human health. Challenges include the need to better elucidate and demonstrate: (1) the links between contaminants in raptors and human health; (2) the utility of raptors for the monitoring of emerging and vector-borne diseases in relation to human health and (3) the utility of raptors for the monitoring of environmental change.

Opportunities include (1) incorporating work on these challenges within future research programmes; (2) making greater use of raptor collections in

museums and specimen banks in addressing these challenges by bringing these collections in to the network and (3) developing the tools needed to read the raptor environmental record from living birds and those that have died from a range of causes.

Areas with potential for development include the utility of raptors to monitor the spread of selected emerging diseases; re-telling the persistent organic pollutants narrative to encompass raptor and human health reproductive, neural and disease issues; the economic and social value of raptors to human well-being as part of the Organisation for Economic Co-operation and Development and EU initiatives on 'Beyond GDP' and better use of scientific collections to get temporal and spatial change and environmental change information, using a range of stable isotopes (e.g. lead, cadmium and mercury).

A new COST Action to develop a European Raptor Biomonitoring Facility, building on the work of EURAPMON, which started in late 2017, is taking forward work in a number of the areas addressed in this paper, including the use of scientific collections for contaminant monitoring in raptors. An EU-funded LIFE project (LIFE APEX) starting in late 2018 will also demonstrate the utility of raptors to monitor contaminants in the environment in relation to the needs of EU chemicals regulations.

Acknowledgements

The authors wish to thank the organisers of the EURAPMON final conference and EURAPMON funding bodies and the Guest Editors of this Special Issue.

Funding

This work was supported by European Science Foundation.

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