Conservation Letter

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Conservation Letter: Raptors and Anticoagulant Rodenticides

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Introduction

Widespread use of anticoagulant rodenticides (ARs) creates an ongoing global conservation concern for raptors. ARs have the potential to negatively affect birds primarily by secondary exposure (via scavenging or depredating primary consumers of ARs), which may cause toxicosis following the consumption of a poisoned prey. Exposure to ARs has been documented in numerous raptor species sampled from a wide range of regions, including North America (Stone et al. 2003, Albert et al. 2010, Thomas et al. 2011, Murray 2017, Gabriel et al. 2018), Europe (Berny et al. 1997, Sanchez-Barbudo et al. 2012, Hughes et al. 2013), Asia (Naim et al. 2010, Hong et al. 2019), and Australia (Lohr et al. 2018). This Conservation Letter provides a scientific review of AR exposure to raptors at this global scale and highlights lessons learned and potential solutions. This letter is not intended as an exhaustive literature review. Rather, the intent of the Raptor Research Foundation (RRF) is to provide readers with enough evidence-based examples that readers can appreciate the scope and prevalence of AR exposure, understand the potential effects on raptor species and populations, and recognize some of the challenges associated with addressing AR exposure in raptors across regions.

ARs are a form of ingested rodent pest control that work by blocking the vitamin K cycle, which inhibits blood clotting and may cause internal bleeding, anemia, hemorrhagic shock, and death (Rattner et al. 2014a, Murray 2017, van den Brink et al. 2018). First generation anticoagulant rodenticides (FGARs) such as warfarin, diphacinone, chlorophacinone, and coumatetralyl may require ingestion through multiple feedings before a lethal dose is reached, whereas second generation anticoagulant rodenticides (SGARs; e.g., brodifacoum, bromadiolone, difenacoum, difethialone, and flocoumafen) are more toxic and only require a single feeding to cause death in target species (i.e., rodents; van den Brink et al. 2018). Due to their effectiveness, ARs are commonly used; in a survey of farmers in Delta, Canada, 72% of respondents reported using some sort of rodent control, most of which (82%) were rodenticides (Hindmarch et al. 2018). In the US, the Environmental Protection Agency (USEPA) reported that homeowners spent $110 million in 2005 on rodenticides (USEPA 2011). The occurrence of ARs is also high in rural areas, where 75–95% of farms may use rodenticides (Tosh et al. 2011, Hughes et al. 2013, Hindmarch et al. 2018). Despite the benefits of this widespread application for pest control, increasing evidence suggests that nontarget species, including raptors, are often exposed to ARs when they consume contaminated prey or tainted carrion (Elliott et al. 2014, Rattner et al. 2014, van den Brink et al. 2018).

Effects of Anticoagulant Rodenticides on Individual Raptors

Secondary AR exposure can be lethal due to severe blood loss and internal hemorrhaging, both of which are associated with organ failure, shock, and death. Rates of mortality due to AR exposure are challenging to quantify in free-living birds because it is difficult to directly link AR exposure to death. In addition, differences in analytical methods and species sensitivity make it difficult to quantify the levels that indicate lethality (Thomas et al. 2011). Liver concentrations are typically measured against the suggest-

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ed lethal range of >0.1–0.2 mg/kg wet weight (Newton et al. 1999, Thomas et al. 2011). However, further research is needed to better understand toxicity thresholds as variability exists among individuals and species (Thomas et al. 2011, Rattner and Mastrota 2018, Roos et al. 2021). Nevertheless, raptor mortality attributable to AR exposure has been well documented (e.g., Stone et al. 1999, Hughes et al. 2013, Murray 2017), with some studies suggesting that older birds may be more at risk due to bioaccumulation (Elliott et al. 2016, van den Brink et al. 2018). Evidence has also been derived from birds that were admitted to wildlife rehabilitation centers and subsequently died after exhibiting signs of lethargy, pallor (i.e., pale mucous membranes), bruising, or profuse bleeding from open wounds, nares, or mouths, all of which are associated with AR exposure (Murray 2011, 2018). These symptoms, as well as the presence of ARs at concentrations near the standard threshold levels, may indicate potential toxicosis of wild, free-living raptors (Thomas et al. 2011).

Experimental approaches in controlled laboratory settings indicate that exposure to ARs may also induce sublethal effects, defined as physiological or behavioral changes linked to trace levels that are too low to directly cause death. Sublethal effects can include delayed blood clotting, anemia, and impaired mobility (Newton et al. 1990, Stone et al. 2003, Rattner et al. 2014a). Sublethal AR exposure, combined with other anthropogenic stressors, potentially predisposes affected raptors to injury, disease, malnourishment, and predation (Rattner et al. 2014b, Herring et al. 2017, Hindmarch et al. 2019). Sublethal effects also may manifest on a molecular and cellular level (Rattner et al. 2014b), as vitamin K is needed for genetic processes including RNA transcription and xenobiotic metabolism (Fraser et al. 2018). More research is needed to fully understand the effects of sublethal exposure to ARs in raptors.

Raptors that live near human populations and also consume rodents, including many species of owls (*Strigidae* spp. and *Tytonidae* spp.), are at high risk of secondary AR exposure (Newton 1990, Slankard et al. 2019). For example, assessments of exposure rates in dead raptors collected along roadsides or following admission to a wildlife rehabilitation center demonstrate that 10–84% of Barn Owls (*Tyto alba*; Newton et al. 1990, Albert et al. 2010, López-Perea et al. 2015, Slankard et al. 2019), 65–100% of Great Horned Owls (*Bubo virginianus*; Albert et al. 2010, Murray 2011, Thomas et al. 2011), 75–92% of Barred Owls (*Strix varia*; Albert et al. 2010, Murray 2011), and 87% of Eastern Screech-Owls (*Megascops asio*; Murray 2011) tested positive for ARs across populations. Variability across populations is likely explained by site-specific differences in AR use, and in habitat and prey availability (Thomas et al. 2011, Hindmarch et al. 2017, Hindmarch and Elliott 2018).

Species with broad dietary breadths, such as Red-tailed Hawks (*Buteo jamaicensis*), are also at risk of AR exposure (Stone et al. 2003, Murray 2011, Abernathy et al. 2018). For example, all 43 Red-tailed Hawks sampled at a wildlife rehabilitation center in Massachusetts tested positive for ARs (Murray 2020), and approximately 60% of liver samples from Red-tailed Hawk carcasses collected across Canada had detectable levels of ARs (Thomas et al. 2011). Numerous other opportunistic raptors are also exposed to ARs, including Common Buzzards (*Buteo buteo*; Berny et al. 1997), Northern Goshawks (*Accipiter gentilis*; Sanchez-Barbudo et al. 2012), and Black Kites (*Milvus migrans*; Sanchez-Barbudo et al. 2012) in Europe, and Bald Eagles (*Haliaeetus leucocephalus*; Stone et al. 2003, Niedringhaus et al. 2021) in North America. ARs have also been detected in raptor species whose dietary preference typically focuses on non-rodent prey, including Short-toed Snake-Eagles (*Circaetus gallicus*) in Europe (Sanchez-Barbudo et al. 2012), and Peregrine Falcons (*Falco peregrinus*) and Sharp-shinned Hawks (*Accipiter striatus*) in North America (Stone et al. 2003). ARs also affect raptor species that are primarily scavengers, including Red Kites (*Milvus milvus*) and Griffon Vultures (*Gyps fulvus*) in Europe (Sanchez-Barbudo et al. 2012), and Turkey Vultures (*Cathartes aura*) in North America (Stone et al. 2003, Kelly et al. 2014). These results suggest that pathways of exposure to ARs for raptors are complex and may include transfer via non-rodent taxa such as birds and insects (Elliott et al. 2014, Rattner et al. 2014b).

Although the aforementioned studies provide insight into the exposure of raptors to ARs, the birds sampled represent a nonrandom subset of wild populations. Therefore, exposure rates at the population level likely differ from those reported. Similarly, exposure rates calculated from birds admitted to wildlife rehabilitation centers may not be representative of exposure levels at the population level (Stone et al. 2003, Albert et al. 2010, Murray 2017, Hindmarch et al. 2018). Unfortunately, assessments of AR exposure in wild-caught birds are scarce, which limits our ability to estimate unbiased AR exposure rates. Of the studies that have sampled free-living birds, Gabriel et al. (2018) demonstrated that 70% of Northern Spotted Owls (*Strix occidentalis caurina*; $n = 10$) and 40% of Barred Owls ($n = 84$) in western North America tested positive for one or more ARs, suggesting that secondary AR exposure is a pervasive issue for at least some raptors. In contrast, only 7.8% ($n = 116$) and 8.2% ($n = 97$) of migrating juvenile Red-tailed Hawks in North America tested positive for ARs in their blood plasma (Abernathy et al. 2018, Kwasnoski et al. 2019). This low AR detection rate may be attributed to both the short half-lives of ARs and the insensitivity of AR analysis in blood (Murray 2020), as well as the sampled birds' migratory status, and the fact that they were young individuals that potentially had not yet bioaccumulated detectable levels of toxicants.

EFFECTS OF RODENTICIDES ON RAPTOR POPULATIONS

Although examples of secondary AR exposure to raptors at the individual level are well documented, evidence for population level effects is absent, warranting further investigation (Rattner et al. 2014b, Herring and Eagles-Smith 2017, Quinn 2019, Roos et al. 2021). However, it has been suggested that the widespread application of SGARs in Canada may have resulted in the direct mortality of 11% of Great Horned Owls submitted to rehabilitation or veterinary centers (Thomas et al. 2011). These estimates considered probabilities of exposure in mostly human-dominated landscapes. Thus, because exposure rates vary across landscapes (Tosh et al. 2011, Hughes et al. 2013, Hindmarch et al. 2018), and because sensitivity to ARs varies among species and individuals (Rattner et al. 2011, 2014b), these estimates are specific to the population studied and may not be representative of other raptor populations from different landscapes. Moreover, the results of that study did not provide evidence of causation. Whether AR exposure manifests into population level effects remains unknown.

Under scenarios where lethal AR exposure could potentially manifest into population level effects, the impacts may be more acute for long-lived species with low reproductive rates (i.e., K-strategists), or those that are threatened or endangered where the removal of a few individuals could have marked effects on the population (Rattner et al. 2014b). For example, AR exposure is of growing concern for many vulnerable species including Golden Eagles (*Aquila chrysaetos*; Herring et al. 2017, Niedringhaus et al. 2021) and Northern Spotted Owls (*Strix occidentalis caurina*; Gabriel et al. 2018) in North America, Spanish Imperial Eagles (*Aquila adalberti*), Red Kites, and Common Kestrels (*Falco tinnunculus*; Roos et al. 2021) in Europe (Howald et al. 1999, van den Brink et al. 2018, Nakayama et al. 2019), and Wedge-tailed Eagles (*Aquila audax*; Pay et al. 2021) in Australia. If population level effects were to occur, a decline in ecosystem functions and services provided by raptors, including scavenging (i.e., removal of carcasses from the landscape), nature-based recreation (e.g., bird watching), and biological control of rodent agricultural pests (Donázar et al. 2016) may ensue. However further research is needed to validate this hypothesis and demonstrate a connection between AR exposure and changes in population growth, survival rate, and reproductive success (Quinn 2019).

MITIGATING THE EFFECTS OF ARS ON RAPTORS

Several countries have implemented regulations pertaining to ARs with the goal of mitigating the effects to nontarget wildlife. For example, in the US, ARs are regulated by the Environmental Protection Agency, which considers human and environmental risks following increased awareness of, and growing public concern for, nontarget exposure to children, pets, and wildlife (Eisemann et al. 2018). Most mitigation efforts have aimed to reduce the risk of nontarget exposure by limiting consumer access to SGARs, with emphasis on proper product labeling and application. However, recent changes to legislation in California have demonstrated this to be ineffective at reducing exposure in bobcats (*Lynx rufus*; Serieys et al. 2015, 2021). For example, although the new legislation requires labels that outline proper use that minimizes potential exposure, many consumers ignore the instructions and continue to expose wildlife to SGARs. Alternatively, some consumers have switched to FGARs, which have no regulations associated with them, but that are toxic to wildlife, as predicted by Rattner et al. (2014a). Additional legislation at state and local levels within the US further controls the use of ARs.

Canada has similar federal regulatory legislation under the Pest Management Regulatory Agency and provinces can further restrict usage. Outside North America, legislation has also been introduced to mitigate the potential for ARs to affect wildlife. For example, the European Union regulates ARs under the Biocidal Products Directive, while the United Kingdom (UK) mandates ARs through the Control of Pesticides Regulations (1986) statute. Notably, the UK has enacted the Campaign for Responsible Rodenticide Use which uses stewardship to promote quality assurance and responsible rodent control aimed at protecting both consumers and wildlife (Campaign for Responsible Rodenticide Use 2020). In New Zealand, ARs are regulated by the Ministry for Primary Industries, while in Australia, AR products are regulated by the Australian Pesticides and Veterinary Medicines Authority and the New South Wales Department of Primary Industries. Although changes are slow to take place, this widespread use of legislation to control the application of ARs is an important step in reducing raptors' exposure to ARs and represents a collective effort to curtail rodenticide use and risk to nontarget species such as raptors (Eisemann et al. 2018).

The risk of secondary AR exposure to raptors can also be minimized by instituting alternative measures to chemical rodent control. Eco-friendly, natural methods can be used as part of an integrated pest management approach which includes, for example, a combination of nontoxic lethal or nonlethal methods (e.g., habitat modification, trapping, and nontoxic repellants; Whitmer 2018). One of the simplest, and often most effective ways to discourage rodents is to identify, locate, and eliminate potential food sources (e.g., accessible trash, open compost bins, fallen bird seed, outdoor pet food) and practice structural exclusion by sealing off potential entry points into buildings (Murray et al. 2018, Whitmer 2018). Any thick and densely growing vegetation should be removed from building perimeters, as the vegetation provides rodents with an ideal habitat in terms of food and shelter (Whitmer 2018). For lethal control, snap traps, bucket traps, electric zappers, CO_2 gas-powered traps, or automatic bolt traps are recommended, and dry ice can be used to plug burrows (Witmer 2018). It is also possible to encourage natural avian predators of rodents through the provision of perches and owl nest boxes (Huysman et al. 2018), but the success of these two methods is largely dependent on other factors such as landscape characteristics and local raptor and rodent prey abundance (Hindmarch and Elliott 2018).

FUTURE RESEARCH DIRECTIONS

The effects of ARs on raptors are well described in scientific literature, but are difficult to quantify and therefore require further study to develop a more complete understanding of sublethal effects at the individual level, including breeding productivity and behavior. How individual-level effects translate into population-level effects is also an important avenue for research and is critical for the conservation of at-risk species. Sensitivity to ARs varies at both the species and individual levels (Murray 2011, Hindmarch et al. 2019) with some individuals affected more than others. Therefore, the development of species sensitivity profiles along with blood-clotting reference values (to estimate blood-clotting time) is needed to better determine how raptor populations may respond to AR exposure. Where possible, an emphasis should be placed on assessments of AR exposure in wild, free-ranging raptors to reduce potential biases introduced to exposure estimates calculated using raptors admitted to wildlife rehabilitation centers. This is especially the case for geographic regions underrepresented in the literature (e.g., South America) where access to resources (e.g., lab equipment, money to process samples) prohibits investigations of AR exposure in the country of study, and where regulations prohibit export of samples to international laboratories (M. Saggese pers. comm.). Nevertheless, we encourage continued assessment of data derived from wildlife rehabilitation centers; such data continues to be instrumental in our understanding of the geographic range and physical effects of ARs on raptors.

Exposure rates and studies of AR effects on raptors have been derived primarily from assessments made in temperate regions of North America and Europe (e.g., Elliot et al. 1996, Hughes et al. 2013, López-Perea et al. 2015, Hindmarch et al. 2017). Although opportunistically collected data from wildlife rehabilitation centers suggest many species are exposed to ARs, empirical studies of AR exposure and studies of the concomitant effects often focus on species used to develop toxicological models for raptors (e.g., Eastern Screech-Owl and American Kestrel [*Falco sparverius*]; Rattner et al. 2010, 2014a), or common species of owls (e.g., Barred Owl; Gabriel et al. 2018) or *Buteo* hawks (e.g., Red-tailed Hawk; Abernathy et al. 2018). The potential for AR exposure appears to be both site- and species-specific (Stone et al. 2003, Hindmarch et al. 2017). Thus, more research is needed from other regions across a broad range of taxa, especially from understudied areas that are critical for raptors (e.g., areas encompassing key migratory routes).

As a leading professional society for raptor researchers and raptor conservationists, the RRF is dedicated to the accumulation and dissemination of scientific information about raptors, and to resolving raptor conservation concerns (RRF 2021). Anticoagulant rodenticide exposure in raptors remains an ongoing conservation concern, potentially presenting a global threat to raptor populations, many of which have little to no direct regulatory protection. Based on the science summarized here, reducing the sources and scale of anticoagulant rodenticide exposure will allow long-term co-occurrence of raptor populations with human populations.

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