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From sport hunting to breeding success: Patterns of lead ammunition ingestion and its effects on an endangered raptor

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HIGHLIGHTS

- Bonelli's eagles ingested lead ammunition from injured small-game prey.
- The ingestion of lead shots was related to lead concentration in feathers.
- Lead ingestion negatively impacted eagles' breeding success.
- Some game modalities should be regulated to reduce raptor exposure to lead.

GRAPHICAL ABSTRACT

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ABSTRACT

Lead is highly toxic for wildlife, with pernicious consequences especially in long-lived predators. The causes of lead ammunition ingestion in Bonelli's eagle (*Aquila fasciata*) and its effects on breeding success were studied in one of the most important populations of this endangered species in Europe. Regurgitated pellets belonging to different pairs from 2004 to 2014 were analyzed, both in the breeding (1363 pellets from 12 territories) and non-breeding (172 pellets from 9 territories) seasons. From these territories, 57 molted feathers to study lead contamination were analyzed, and breeding success was monitored for 41 breeding attempts. The occurrence of lead shots in pellets was detected using X-ray photographs. Pellets were also used to describe eagle diet. Lead shots in pellets were present in 83.3% of the territories. The frequency of occurrence of lead shots in pellets (2.81% in spring and 1.31% in autumn) was primarily related to the consumption of red-legged partridge in the breeding season (when partridges are hunted from blinds using calling lures), and secondarily to rabbit consumption in the non-breeding season (coinciding with the main hunting season). Thus, our results indicate that injured small-game were the main source of lead contamination in the Bonelli's eagle. For the first time for a raptor species, a positive relationship between the frequency of occurrence of lead shots in pellets and lead concentration in eagles' feathers has been documented. Lead concentration in feathers (mean ± SD: 816 ±

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426 μg kg^{-1}, with no sex-related differences) was high for a species that rarely eats carrion or aquatic birds (the main prey-related lead source for raptors). This had negative effects on breeding success, which could jeopardize Bonelli's eagles in other European populations that are sustained by juvenile dispersal from the study population. Our work shows that some game modalities pose a potential threat to endangered raptors.

1. Introduction

Birds of prey, especially large ones, are among the most threatened vertebrate groups in the world (Sekercioglu, 2006). This is a matter of concern not only for conservationists, but also for ecologists because raptors serve important functions in ecosystems such as stabilizing predator–prey dynamics (Ives and Dobson, 1987) and favoring species richness via competitive coexistence (Brown et al., 1988). In fact, birds of prey are spatially associated with biodiversity-rich areas (Sergio et al., 2005), and thus efforts to conserve raptors can benefit many other species. In addition, the decline of raptor populations has wide implications for policy makers and society as a whole, given that raptors provide many regulating (e.g., rodent pest control and removal of livestock carcasses) and cultural (e.g., ecotourism and aesthetic inspiration) ecosystem services to humans (Sekercioglu, 2006; Whelan et al., 2008; Donázar et al., 2016).

The decline in raptor populations has several causes, including habitat degradation and loss, persecution by humans (e.g., through shooting and deliberate poisoning), mortality associated with power lines and windfarms, and contamination with toxic chemicals (Donázar et al., 2016). Among contaminants, compounds such as DDT (an organo chlorine used as a pesticide) and diclofenac (a veterinarian drug) have had devastating effects on many raptor species in the last few decades (Newton, 1979; Pain et al., 2003). This has led to huge and coordinated efforts by researchers, managers and legislators to prevent the release of these contaminants into the environment (e.g., Ratcliffe, 1972; Hamerstrom et al., 1975; Cuthbert et al., 2011). However, there are many other widely used products whose effects have been less investigated. This is the case for heavy metals such as mercury, cadmium, arsenic and lead, which can alter critical physiological functions and have lethal effects on raptors (Newton, 1979). Due to the bioaccumulation potential of some of these metals, species from the highest trophic levels, such as raptors, are at greater risk (Miller et al., 2002).

Poisoning due to lead intoxication is an increasing concern to raptor ecology and conservation. Lead ammunition is probably the most relevant source of lead poisoning in raptors (García-Fernández, 2014). Avian predators and especially scavengers, can ingest lead from ammunition (shots or bullet fragments) present in big- and small-game prey that have been shot but not collected by hunters (Fisher et al., 2006). In raptors, after ingestion, lead is dissolved by the low pH of their stomachs and then absorbed, distributed and accumulated into the organism in the form of Pb^{2+} ion that easily replaces the Ca^{2+} ion (Scheuhammer, 1987). Following a multicompartmental kinetic model (García-Fernández, 2014), this lead spreads through different internal tissues (e.g., liver, kidney, bones and brain; García-Fernández et al., 2008; Gangoso et al., 2009), as well as eggs and feathers (García-Fernández et al., 2008).

Given that game hunting is a widespread and growing practice worldwide (Fisher et al., 2006), understanding the patterns of lead ammunition ingestion by birds of prey is increasingly important. However, while lead poisoning has been well studied in aquatic birds (see e.g. Haig et al., 2014), little is known about lead poisoning in raptors. In this group, the risk of lead ingestion seems to be closely associated with hunting activity (see Fisher et al., 2006 and references therein) and can threaten the survival of critically endangered species (Finkelstein et al., 2012). Among raptors, major gaps in knowledge are related to: how the different game modalities impact ammunition ingestion; the quantitative relationships between such ingestion patterns and lead contamination in tissues; and the relationship between the presence of lead in tissues and demographic parameters such as breeding success (see review by Haig et al., 2014). In addition, non-scavenging raptors, which are largely insensitive to lead contamination of big game, have received less scientific attention.

Spain, which holds a rich community of raptors and supports intense sport hunting activity, is a paradigmatic scenario for hunting-conservation conflicts (Moleón et al., 2011). Currently, the number of hunting licenses is ca. 1.078.852 and hunting areas represent more than half of the national territory (Ministry of Agriculture, Food and Environment, 2010). Among small game, the red legged partridge (*Alectoris rufa*) is the most sought after species in Spain, with three million partridges being shot every year. The European rabbit (*Oryctolagus cuniculus*) is also an important game species (ca. six million rabbits shot every year; Ministry of Agriculture, Food and Environment, 2010). Hares (*Lepus* spp.), wood pigeons (*Columba palumbus*), turtledoves (*Streptopelia turtur*), corvids, thrushes (*Turdus* spp.) and other avian species are hunted less frequently. The main small game hunting methods are hunting in hand (normally, 2–6 hunters) and hunting jump (one hunter assisted by one or several pointing dogs), and the main hunting season is from August to December (Gómez, 1991). In addition, partridges are also hunted using calling lures (wild partridge males attracted to a singing captive male placed in front of a hidden hunter) outside of the standard hunting season, between January and March, which coincides with the first stage of the breeding period in raptors (Moleón et al., 2011).

The use of lead ammunition is being increasingly regulated internationally (e.g. Haig et al., 2014). In Spain, its use has been banned since 2001 in wetlands (Royal Decree 581/2001), where lead shots must be replaced by steel shots (Watson et al., 2009). However, the use of lead ammunition remains widespread outside of wetlands. Not surprisingly, lead ingestion and poisoning have been documented in a number of raptor species in Spain (Cerradelo et al., 1992; Hernández, 1995; Mateo et al., 1997, 1999, 2001; Mateo et al., 2003; García-Fernández et al., 2005; Gangoso et al., 2009). However, many other species remain unexplored, and the causes and consequences of lead ingestion are notably unknown.

Our general aim was to investigate the patterns, causes and effects on breeding success of lead ingestion in Bonelli's eagles (*A. fasciata* Vieillot, *1822*) in southeastern Spain using non-intrusive methods. Spain holds 80% of the European breeding population of this endangered territorial species (Real, 2004; Del Moral, 2006). The Bonelli's eagle is a good study model because, as many other Iberian raptors of medium and large size, it bases its diet on small game species (Moleón et al., 2008, 2009a). The present study was focused on a study area that supports intensive small game hunting (Moleón et al., 2011). The studied Bonelli's eagle population is among the most dense and productive populations of the species in Europe (Gil-Sánchez et al., 2004; Moleón and Gil-Sánchez, 2006) and acts as a demographic source that supports other Western European populations through dispersal processes (Hernández-Matías et al., 2013). Thus, our study could provide important insights to conserve endangered raptors beyond the study population and species.

Following an integrative framework, we investigated: 1) the ingestion rates of shot pellets by Bonelli's eagles; 2) the relationship among shot ingestion and prey species, which are associated with different