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CONTRIBUTED PAPER

Persistent lead poisoning of waterfowl in the Camargue (southern France) 10 years after the ban on the use of lead ammunition in wetlands

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Abstract

Lead pollution is a worldwide environmental and health issue causing persistent detrimental effects on humans and wildlife. Despite having been identified as detrimental to waterfowl a century ago, in France lead shotgun pellets for hunting were banned only in 2006 and only in wetlands. We used long-term monitoring data from the Camargue (southern France) to (1) assess the local effectiveness of the French regulation at reducing the ingestion of lead shotgun pellets by waterfowl and to (2) assess local hunter compliance with the regulation. We used data on 2187 gizzards from 13 waterfowl species collected from 38 hunters in the Camargue over 20 hunting seasons (1998 to 2017). In addition, from 2008 to 2019, we systematically collected shotgun shell cases at three communal wetland hunting sites and used the ratio of cases indicating lead versus nontoxic shotgun shells to estimate hunter compliance with the ban. Across the 20-year study period that spanned pre- and post-ban, gizzards of harvested waterfowl had a mean lead shotgun pellet prevalence of 12% across the 13 species with no significant reduction over time. There was a slow increase in the use of nontoxic shot shells after the ban; lead shells continued to be used widely, suggesting inadequate policy enforcement. Because the ban was only applied for hunting in wetlands, hunters have to be caught with lead shells in the shotgun while in wetland to be fined. It is still legal to carry lead shells, favoring the circumvention of the regulation. Our results support the need for a complete ban of lead shotgun shells for both wetland and terrestrial hunting. A complete ban would facilitate policy enforcement and would favor compliance, eventually leading to a phase-out of lead shell production and use.

KEYWORDS

ammunition, hunting, policy enforcement, pollution

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1 | INTRODUCTION

Lead pollution is a worldwide health issue for people, wildlife, and the environment, causing persistent detrimental effects (Larsen & Sánchez-Triana, 2023; Pain et al., 2019). In particular, lead poisoning negatively affects wildlife populations by increasing mortality rates (Pain et al., 2019). In birds, from waterfowl to raptors, there is a negative correlation between population growth rates and lead ingestion rates (Green et al., 2022; Green & Pain, 2016; Meyer et al., 2016). Several national and international public policies have been implemented to reduce the risks of lead contamination (Avery, 2009; Stroud, 2015). Lead ammunition for hunting is one of the largest sources of lead in the environment in Europe. A major issue is the poisoning of waterfowl that ingest lead shot as grit while foraging in wetlands. Despite this issue having been identified over a century ago (Bellrose, 1959; Bowles, 1908; Hoffmann, 1960; Wetmore, 1919), considerable scientific evidence and advocacy were required before policy regulations aimed at removing this threat were proposed and implemented (Arnemo et al., 2016).

In Europe, the use of lead shotgun shells was first banned in 1986 in Danish wetlands listed under the Ramsar convention (Mateo & Kanstrup, 2019). Later, many European countries introduced national legislation following the African-Eurasian Waterfowl Agreement (AEWA) recommendation to use nontoxic shotgun shells in wetlands (Avery, 2009). Compliance with bans on lead shotgun shell use for waterfowl hunting or for hunting over wetlands has been variable. For instance, there are low levels of compliance in some countries, such as England (Stroud et al., 2021), while other countries, such as Denmark (Kanstrup & Balsby, 2019), have a high level of compliance. Denmark has had a complete ban on the use of lead shotgun shells since 1996 (Mateo & Kanstrup, 2019).

In France, the use of lead shotgun shells for hunting in wetlands was banned in 2006 (Mondain-Monval et al., 2015). It remained legal to use lead shotgun shells in terrestrial habitats, however, and to carry (but not use) lead shotgun shells while hunting in wetlands. This made the ban on lead shells in wetlands difficult to police and to enforce. We are unaware of any evaluation of the effectiveness of this French regulation at reducing waterfowl exposure to lead shotgun pellets and lead poisoning (see Mondain-Monval et al. (2015) for the Camargue), nor of hunter compliance at the national scale (Mondain-Monval et al., 2020).

The Camargue is the largest wetland in France (145,000 ha), and a major migration and wintering area for waterbirds in Europe (Galewski & Devictor, 2016). Classified as a Ramsar site, the Camargue is home to tens of thousands of waterfowl every winter (Tamisier & Dehorter, 1999). The Camargue has a long tradition of waterfowl hunting; each year several thousand hunters harvest waterfowl in the delta (Mondain-Monval et al., 2009). This major historical hunting has resulted in significant lead contamination of the marshes (Pain, 1992) and of waterfowl (Hoffmann, 1960; Hovette, 1973; Mondain-Monval et al., 2002; Mondain-Monval et al., 2015; Pain, 1990; Pirot & Taris, 1987). Several waterfowl species wintering in the Camargue are now considered vulnerable or near threatened according to the European IUCN red list (Common pochard *Aythya ferina*, Northern Pintail *Anas acuta*, Common snipe *Gallinago gallinago*, and Common coot *Fulica atra*; Birdlife International 2021). A long-term study of wintering populations of several duck species in the UK identified the Common pochard and the Northern pintail as the species with the highest estimated mortality rates from lead poisoning and also the most severe population declines (Green & Pain, 2016). Hence, identifying the remaining causes of lead poisoning is critical to mitigate this threat.

In this study, we used long-term data on lead shotgun pellet ingestion by waterfowl in the Camargue (Mondain-Monval et al., 2002) to (1) assess the local effectiveness of the French regulation at reducing lead shotgun pellet ingestion by waterfowl, and (2) assess the local compliance with the lead shotgun shell ban in wetlands starting in 2007. We analyzed the content of waterfowl gizzards to assess changes in lead shotgun pellet consumption. We also identified shell cases found along hunting trails to assess hunter compliance with the regulation. Our study provides the first assessment of lead shotgun pellet ingestion in France since the ban in a region with high waterfowl hunting pressure. We propose operational policy changes to improve hunter compliance and decrease lead contamination in the environment.

2 | MATERIALS AND METHODS

Waterfowl exposure to lead shotgun pellets is commonly assessed by examining their gizzards to quantify the number of ingested lead vs. nontoxic pellets (Mondain-Monval et al., 2015). We collected bird gizzards opportunistically from a network of hunters in the Camargue during each hunting season from 1998/1999 to 2017/2018 (Figure 1). A total of 38 hunters contributed to the sampling effort. Those hunters harvested waterfowl both on communal hunting grounds (managed by the local hunting associations) and on private hunting estates. The number of gizzards collected per winter varied from 3 to 305, with a mean of 115 ± 20 (SE). In total, we collected

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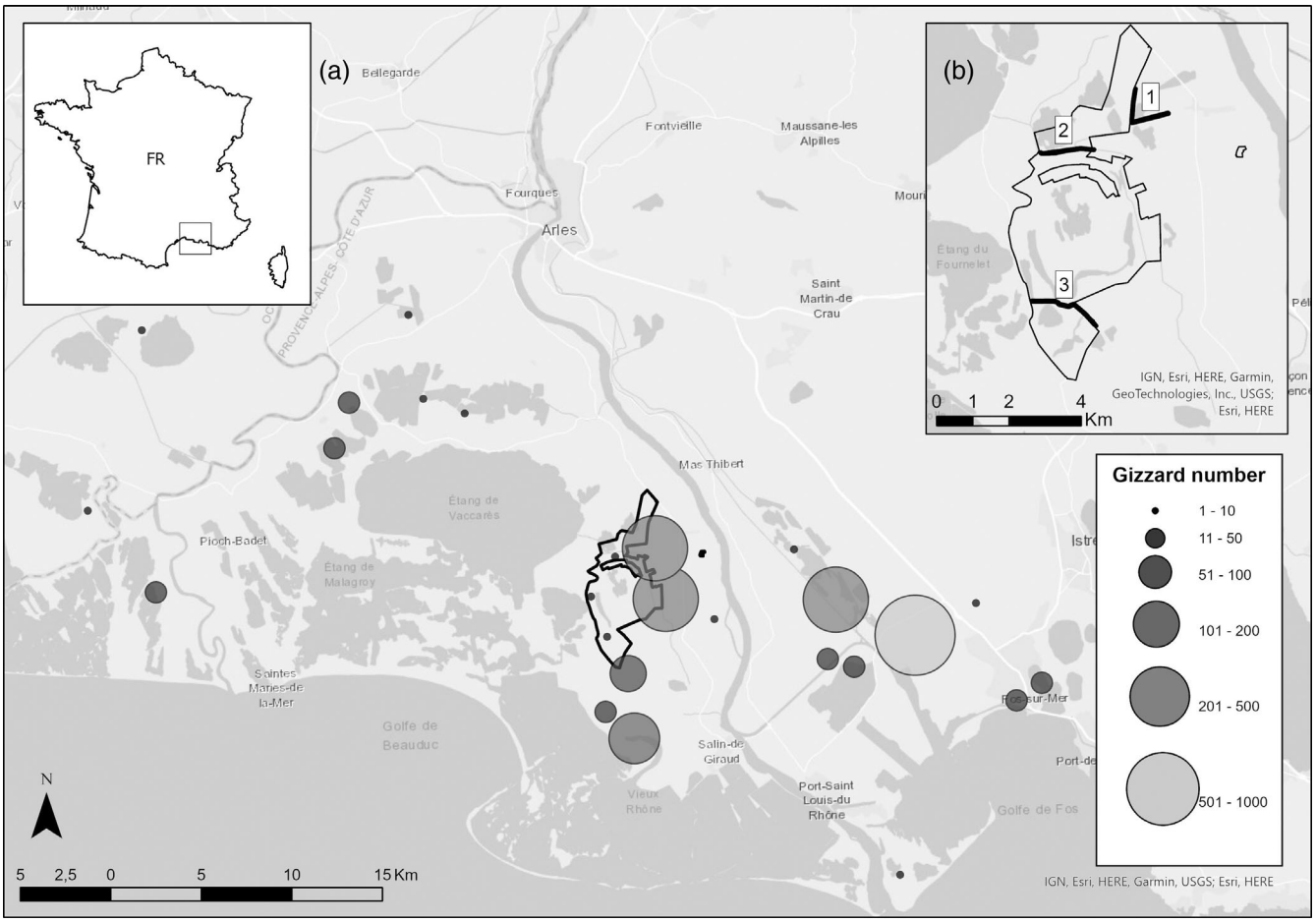


FIGURE 1 Location of the Camargue study site in southern France (insert). (a) Origin of the gizzards from birds collected by hunters during the hunting seasons 1998/1999 to 2017/2018 in the Camargue. Circle size indicates the number of gizzards collected at each location. (b) Location of the communal hunting trails where shell cases were collected in the vicinity of the Tour du Valat nature reserve: (1) Draille du Sambuc, (2) Bordure du Fumemorte and (3) Draille marseillaise.

2306 gizzards from 28 species, which represent well the community of wintering game species in the Camargue (Data S1).

For each collected gizzard, we recorded the species, date, and exact location of harvest. Gizzards were frozen for later analysis. Gizzards were first examined to detect wounds. It was sometimes difficult to establish whether a steel pellet found in the gizzard was embedded (having penetrated through the flesh when the bird was shot) or ingested (swallowed by the bird as grit) because embedded steel pellets keep their round shape while lead pellets tend to flatten on impact. Hence, we considered uneroded shot of any type found in a wounded gizzard as embedded. Then, we cut gizzards in half and washed the contents into a dish with a stream of water. Plant material and other food items were removed by flotation and carefully inspected for grit (including shotgun pellets); the grit was retained in the dish. We examined the remaining gizzard contents with x-ray photography to ensure we detected all shotgun pellets (Montalbano & Hines, 1978). We considered shotgun pellets attracted by a magnet to be steel. To identify lead shotgun pellets and the metal or alloy composition of other pellets, we analyzed all pellets not attracted by a magnet with an X-ray fluorescence spectrometer (Thermo Scientific XL3t 980 GOLDD+, Niton Corp.). We used a 3 mm X-beam, the metal alloys calibration mode, and Kapton support. We classified shotgun pellets as nontoxic when they were made of steel, bismuth, tungsten, tin, or an alloy of these metals based on an extensive toxicology survey (see https://www.fws.gov/story/2022-04/nontoxic-shot-regulations-hunting-waterfowl-and-coots-us).

Every hunting season from 2008/2009 to 2019/2020, we collected shell cases at three public wetland hunting sites located on the outskirts of Tour du Valat nature reserve (Figure 1; 43°30′30″ N, 4°39′59″ E) where it is illegal to hunt with lead shotgun shells. We collected shell cases abandoned by hunters on the ground by walking twice during each hunting season along the 5.2 km of hunting paths (Draille du Sambuc, bordure du

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Fumemorte, and Draille marseillaise; Figure 1) where the communal hunters of Arles hunt (Groupe Cynégétique Arlésien). We used the same research effort and the same observer over the study period. We considered only recent, bright shell cases (no rusty marks that appear after a season). We distinguished lead and nontoxic shells from the inscription on the shell cases (Mondain-Monval et al., 2020). Shell reloading is not practiced in our region, so shell case inscriptions reflect their content.

All materials were collected in accordance with French and European legislation, including the 2009/147/EC Directive, and Human and Animal Rights that were fully respected.

3 | STATISTICAL ANALYSES

3.1 | Data preparation and variables

3.1.1 | Gizzard dataset

Because terrestrial species (i.e., European turtle dove *Streptopelia turtur*, Common pheasant *Phasianus colchicus* and Common quail *Coturnix coturnix*) were not the targets of the lead ban, we removed them from the analyses. We only retained the game species with more than five gizzards collected. Because we aimed to assess the effect of the lead ban on lead contamination, we only retained species for which there was at least one lead shotgun pellet detected (Table 1). Hence, gizzards of Garganey *Spatula querquedula*, Tufted duck *Aythya fuligula*, Red knot *Calidris canutus*, Black-tailed godwit *Limosa limosa*, Red-crested pochard *Netta rufina*, Eurasian Curlew *Numenius arquata*, Whimbrel *Numenius phaeopus*, Eurasian golden plover *Pluvialis apricaria*, Common greenshank *Tringa nebularia*, Redshank *Tringa totanus*, and Northern lapwing *Vanellus vanellus* were removed, so that the final dataset contained 13 species (see Data S1 for shotgun pellets found in the 28 species collected, including landbirds).

We measured gizzard lead contamination using two metrics: (1) *lead pellet prevalence* (the proportion of gizzard containing at least one lead pellet) because toxicity starts with the first ingested lead pellet (Tavecchia et al., 2001) and (2) the *number of lead pellets* in gizzards because we hypothesized that a decrease in the number of *pellets* may precede a decrease in *lead pellet prevalence*. The corrosion rate in gizzard of commercial lead shot is approximately 5 mg per day, which does not differ significantly from the corrosion rate of steel shots (Kimball & Munir, 1971; Krone et al., 2019).

To assess the replacement of lead by nontoxic shotgun pellets as grit used by birds, we modeled the prevalence and the number of nontoxic shotgun pellets found in each gizzard. To control for variation in both prevalence and number of shotgun pellets ingested as grit that may be caused by species traits (i.e., diet or taxonomic family), we used the latter factors as covariates in the models (Table 1). We determined diet following Cramp et al. (1988) with four categories (granivorous, carnivorous, omnivorous, and herbivorous; Data S1) for the initial dataset (28 species) and reduced it to two categories (omnivorous or herbivorous) for the reduced dataset (13 species). Also, because we did not find any nontoxic shots in Scolopacidae, we reduced the family from three to two categories: Anatidae versus Others (Rallidae and Scolopacidae pooled).

TABLE 1 Species retained for the analysis of the effect of the ban on lead shotgun shells on gizzard content in waterbirds of the Camargue (1998/1999 to 2017/2018) with their diet, family, number of gizzards (N), number of gizzards containing at least one lead pellet N (lead) and at least one nontoxic shotgun pellet N (nontoxic).

Species	Diet	Family	*N*	*N* (lead)	*N* (nontoxic)
Anas acuta	Omnivorous	Anatidae	19	6	2
Anas crecca	Omnivorous	Anatidae	546	75	23
Anas platyrhynchos	Omnivorous	Anatidae	337	102	30
Anser anser	Herbivorous	Anatidae	86	5	15
Aythya ferina	Omnivorous	Anatidae	23	4	0
Fulica atra	Herbivorous	Rallidae	130	11	4
Gallinago gallinago	Omnivorous	Scolopacidae	144	13	0
Gallinula chloropus	Omnivorous	Rallidae	150	11	6
Lymnocryptes minimus	Omnivorous	Scolopacidae	86	3	0
Mareca penelope	Herbivorous	Anatidae	47	2	0
Mareca strepera	Herbivorous	Anatidae	214	10	8
Rallus aquaticus	Omnivorous	Rallidae	219	13	0
Spatula clypeata	Omnivorous	Anatidae	186	26	7

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3.1.2 | Shell cases dataset

We modeled the proportion of lead shell cases found in the total number of shell cases collected during a given hunting season as a function of time.

3.2 | Model fitting and inferences

3.2.1 | Gizzard dataset

We modeled variation in *lead* shotgun *pellet prevalence* using generalized linear mixed models (GLMMs with logit link and prevalence as binary response variable) with ban period (before or after season 2006/2007), year (as a continuous variable), diet, and family as fixed effects, and species identity as a random effect. We included the interactions between ban and diet, and between ban and family to assess possible differences in the effect of the ban caused by species functional traits or phylogeny. GLMMs were modeled using the package glmmTMB in R (Magnusson et al., 2020).

Because the effect of the ban on *lead* shotgun pellet *prevalence* may be delayed, either because of poor hunter compliance with the new policy or because of lead shotgun pellets persistence in wetlands (Kanstrup et al., 2020), we tested for a decrease in the *prevalence* and *number* of lead shotgun pellets in the gizzards from winter 2007 onward. We used a binary response variable for *pellet prevalence* and a negative binomial distribution for the *lead shotgun pellet number*. No interaction was modeled at this step. We also assessed nonlinear trends in lead shotgun *pellet prevalence* with GAMM models with the same structure as the generalized linear mixed model and applying a thin plate regression spline smooth function on the continuous variable. GAMMs were run using the package mgcv in R (Wood, 2001).

We modeled the variation of *nontoxic* shotgun *pellet prevalence* using generalized linear mixed models with the same structure as above (including interactions between ban and diet, and between ban and family). We evaluated if there was any trend in nontoxic shotgun pellet *prevalence* in the gizzard both for the whole study period and from 2007 onward (no interaction was then included). We also modeled the variation in *nontoxic* pellet *numbers* over the whole study period and from 2007 onward and assessed the improvement of the models with smoothing terms using the same approach as for lead pellets.

We ran models with all combinations of effects (including interactions between ban and diet, and between ban and family for models over the whole study period) that could be derived from the general model using the dredge function in R (Bartón, 2015). We ranked models using the Akaike information criterion (AICc; Burnham and Anderson 2002). We deemed the effects of variables to be significant when the 95% confidence intervals of their estimate did not include 0. Effects are given ± one Standard Error (SE). The AICc of models with a smoothing function were compared to the AICc of models without the smoothing effect run with the same mgcv package.

3.2.2 | Shell cases dataset

We modelled the proportion of lead versus nontoxic shell cases found with a simple logistic model assessing the effect of year as a continuous variable. We used the glm function of the R Stats package. Effects were considered significant when the 95% confidence intervals of their estimate did not include 0.

4 | RESULTS

4.1 | Gizzard dataset

The reduced dataset resulted in 2187 gizzards from 13 species (Table 1). Overall, 281 gizzards contained one or more lead shotgun pellets, and 96 contained one or more nontoxic shotgun pellets. The number of ingested lead pellets ranged from 0 to 104. For the 281 birds with at least one ingested lead pellet, the mean number of lead shotgun pellets per gizzard was 3.97 ± 0.55 (SE).

Fluorescence analysis revealed one bismuth shotgun pellet in a gizzard also containing both lead and steel shotgun pellets and 14 pellets made of an alloy. In 12 of these alloy pellets we found lead so they were in fact "improved lead shotgun pellets." All alloy pellets were found in gizzards containing at least one lead pellets hence we did not analyze the change in prevalence of alloy pellets through time (Data S2).

Model selection indicated that *lead* shotgun pellet *prevalence* in bird gizzards was similar before and after the ban for all species (0.12 ± 0.008 vs. 0.12 ± 0.013; Figure 2). The only explanatory variables retained in the most supported model (Table 2A) were the covariates diet and family. There was a significantly higher *prevalence* of lead pellets in omnivorous than in herbivorous species, and a significantly lower *prevalence* of lead pellets in Rallidae than in other families (Table 2A). Overall, mean lead shotgun pellet *prevalence* was 0.12 ± 0.007, but it varied considerably among species [range: 0.03–0.31] with *Anas acuta* and *Anas platyrhynchos* likely driving the diet effect as omnivorous species with 0.31 ± 0.10

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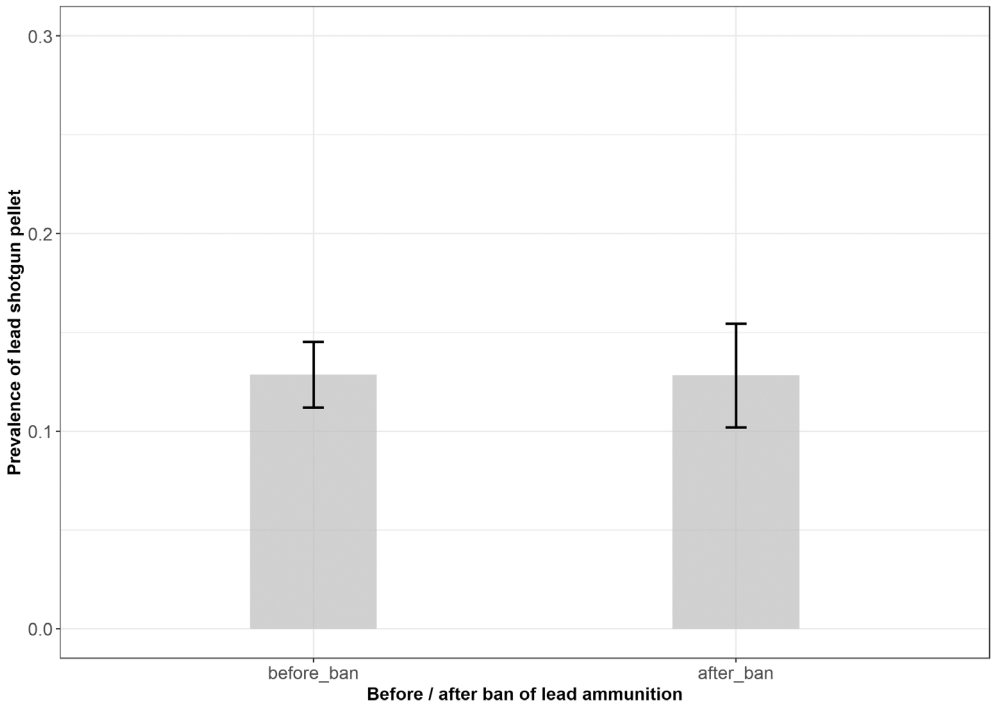


FIGURE 2 Prevalence (±SE) of lead shotgun pellets found in the gizzards of the 13 waterbird species hunted in the Camargue (south of France) from hunting season 1998/1999 to 2017/2018 compared before ($n = 1563$) and after the ban ($n = 624$) on lead ammunition. All species are pooled together.

TABLE 2 Models, ΔAICc and estimates of effects (± SE), for the variation of *lead* shotgun *pellet prevalence* (proportion with at least one shotgun pellet-models with logit link) and *number* (models with negative binomial distribution and log link) in the gizzards of the 13 species hunted in the Camargue before and after the ban on lead shells.

Model	ΔAICc	Intercept	Diet (herbi)	Family	Ban (before)
(A) Lead pellet prevalence over the whole period (1998/1999 to 2017/2018)					
Intercept + diet + family	0	−1.56 ± 0.26	−1.02 ± 0.41	Rall: −0.67 ± 0.42 Scol: −1.13 ± 0.51	
Intercept + diet + family + ban	3.91	−1.54 ± 0.28	−1.02 ± 0.41	Rall: −0.67 ± 0.42 Scol: −1.13 ± 0.54	−0.02 ± 0.15
(B) Lead pellet prevalence after the ban (2007/2008 to 2017/2018)					
Intercept + diet + family	0	−1.14 ± 0.30	−1.73 ± 0.55	Rall: −1.49 ± 0.5 Scol: −1.54 ± 0.75	
Intercept + diet + family + year	3.62	−1.13 ± 0.29	−1.81 ± 0.55	Rall: −1.49 ± 0.49 Scol: −1.51 ± 0.74	0.10 ± 0.12
(C) Lead pellet number after ban (2007/2008 to 2017/2018)					
Intercept + diet + family	0	−0.23 ± 0.39	−1.69 ± 0.60	Rall: −1.45 ± 0.53 Scol: −1.54 ± 0.83	
Intercept + diet + family + year	3.49	−0.17 ± 0.49	−1.82 ± 0.69	Rall: −1.48 ± 0.58 Scol: −1.58 ± 0.96	0.11 ± 0.11

Note: Only the most supported models and the first model in the list with one of the effects of interest (ban or year) are presented for each modeling set (see Data S3–S5 for the full set of models run). (A) The intercept estimates the mean prevalence for omnivorous species of the Anatidae family. (B) The intercept estimates the mean prevalence for omnivorous species of the Anatidae family. (C) The intercept estimates the mean number of pellets for omnivorous species of the Anatidae family. Estimates of effects are for species with a herbivorous diet, for Rallidae and Scolopacidae.

and 0.30 ± 0.02 lead shotgun pellet *prevalence*, respectively (Figure 3).

After the ban, we did not detect any linear decrease of *lead* shotgun pellet *prevalence* in gizzard nor any linear decrease in lead shotgun pellet *numbers* in gizzards containing at least one lead shotgun pellet (Table 2B,C). Assessing a smoothing effect on the trend for *prevalence* resulted in an effective degrees of freedom (edf) equal to 1, hence equivalent to a linear relationship (ΔAICc with the model without smoothing = 2.04). Similarly, the

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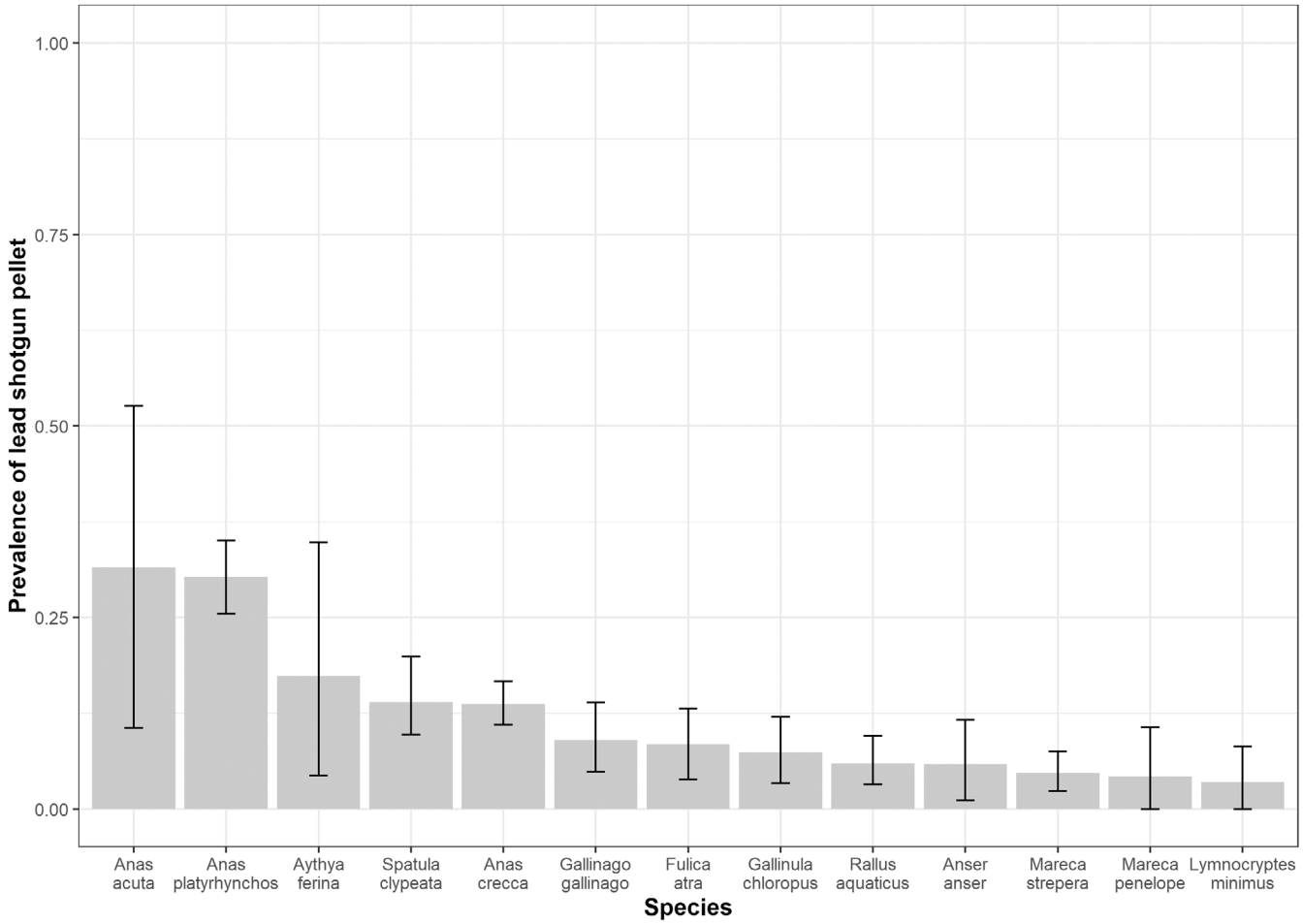


FIGURE 3 Prevalence estimate (±SE) of lead shotgun pellets found in the gizzards of the 13 waterbird species hunted in the Camargue (south of France) from hunting season 1998/1999 to 2017/2018.

smoothing effect did not provide a better model for the *number* of lead shotgun pellets in gizzards relative to a model without smoothing (edf = 8, ΔAICc = 463 with the model without smoothing). In both models after the ban, only diet and family explained differences in lead shotgun pellet *prevalence* and *numbers* in gizzards with a negative effect of both an herbivorous diet and family Rallidae (Table 2B,C).

Regarding *nontoxic* shotgun pellets, model selection did not show any effect of the lead ban on *prevalence* (Table 3A). After the ban, nontoxic shotgun pellet *prevalence* and *numbers* in gizzards did not show any increase (Table 3B,C). Adding a smoothing function worsened the model (edf = 1 and ΔAICc >2 in both cases). Modeling an effect of year on the *number* of nontoxic shotgun pellets in gizzards over the whole study period (1998–2017) showed a significant slight increase ($\beta = 0.05 \pm 0.02$), but this model was, however, considered equivalent to the null model (ΔAICc = 1.39). Adding a smoothing effect on year did not improve the fit of the model (edf = 3.2, ΔAICc = 0.80).

4.2 | Shell cases dataset

We retrieved 3966 shell cases from the communal hunting trails surrounding the Tour du Valat nature reserve. Markings were visible enough on all of them to be classified as nontoxic or lead shells. The logistic model suggested a significant linear decrease in the proportion of lead shotgun shells used by hunters through time (effect of year: $\beta = -0.047 \pm 0.0073$, $p < 0.0001$) from 2008 onwards. The proportion of lead shells remained high, with more than half of the shells found in 2018 and 2019 being lead (Figure 4).

5 | DISCUSSION

We did not find a significant reduction in the prevalence and number of lead shotgun pellets ingested by waterfowl in the Camargue in the 10 years following the 2006 ban on the use of lead shotgun pellets for hunting in wetlands in France. Gizzards of harvested waterfowl were as

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TABLE 3 Models, ΔAICc and estimates of effects (±SE), for the variation of *nontoxic* shotgun pellet *prevalence* (A & B, models with logit link) and *number* (C, models with negative binomial distribution and log link) in the gizzards of the 13 species hunted in the Camargue before and after the ban on lead shells.

Model	ΔAICc	Intercept	Diet (herbi)	Family	Ban (before)
(A) Nontoxic pellet prevalence over the whole period (1998/1999 to 2017/2018)					
Intercept + family		−2.96 ± 0.48		−1.75 ± 0.85	
Intercept + family + diet + ban	2.84	−3.13 ± 0.68	0.49 ± 0.92	−1.75 ± 0.96	−0.07 ± 0.25
(B) Nontoxic pellet prevalence after the ban (2007/2008 to 2017/2018)					
Intercept + family + diet		−3.31 ± 0.63	1.29 ± 0.75	−0.6 ± 0.75	
Intercept + diet + year	2.62	−3.47 ± 0.48	1.21 ± 0.66		0.18 ± 0.17
(C) Nontoxic pellet number after the ban (2007/2008 to 2017/2018)					
Intercept + diet		−3.25 ± 0.51	1.38 ± 0.68		
Intercept + diet + year	2.67	−3.20 ± 0.49	1.28 ± 0.66		0.17 ± 0.16

Note: Only the most supported models and the first model in the list with one of the effects of interest (ban or year) are presented for each modeling set (see Data S6–S8 for the full set of models run). (A) The intercept estimates the mean prevalence for omnivorous species of the Anatidae family after the ban. (B) The intercept estimates the mean prevalence for omnivorous species of the Anatidae family across years. (C) The intercept estimates the mean number of pellets for omnivorous species of the Anatidae family through years. Estimates of effects are for species with a herbivorous diet, and for family other than Anatidae.

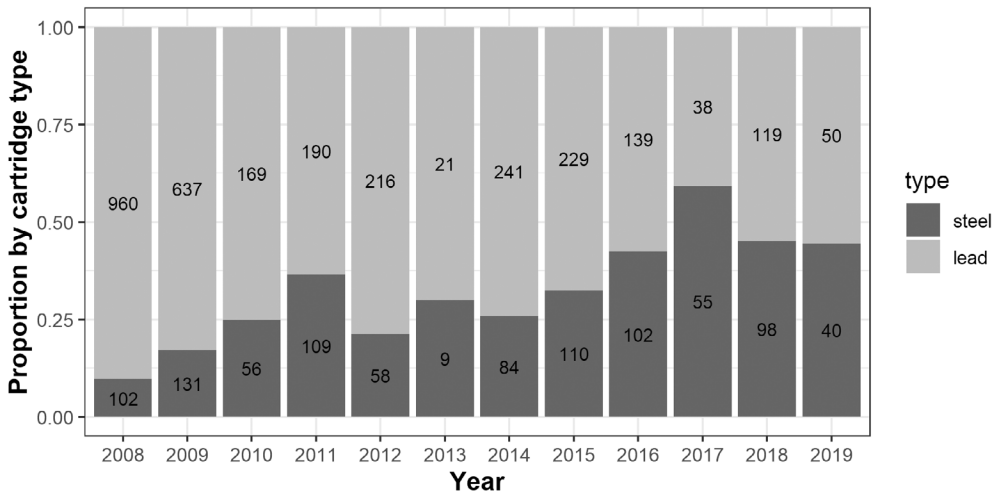


FIGURE 4 Proportion of lead and nontoxic shell cases found at communal hunting trails surrounding Tour du Valat in the Camargue for the hunting season between 2008/2009 and 2019/2020. Values in the columns indicate the total number of shells of each type each year.

likely to contain at least one lead shotgun pellet before than after the ban, with a mean prevalence of 12% for 13 species across the study period. Because the survival of mallards decreases from the first lead pellet found in the gizzard (Tavecchia et al., 2001), the negative expected demographic impact of lead contamination for wintering waterfowl in the south of France is likely to continue.

The stability in the incidence of lead shotgun pellet ingestion may stem from three non-exclusive causes. First, the birds killed and analyzed in this study do not only feed in the marshes of the Camargue and may have been contaminated elsewhere, in particular in countries without regulations on lead shotgun shells. Indeed, several long-distance migratory species (e.g., Eurasian teal *Anas crecca*) are likely to ingest lead while feeding during their migration across Russia and northern Europe. The mallard *Anas platyrhynchos* (a similar granivorous species but mostly resident in the region; Guillemain et al., 2015), however, has a higher lead prevalence (30%) than the migratory Eurasian teal (13%), suggesting that lead contamination is occurring largely locally. Further, the retention time of pellets in the gizzards of ducks is variable, depending on diet and other factors, but is typically short (a few weeks), so detection of lead pellet ingestion at sites remote from the Camargue is less likely than for locally ingested pellets (Kerr et al., 2010; Krone et al., 2019).

Second, the local prevalence of lead pellets in gizzards may result from old contamination of wetlands, when lead shells were authorized. Indeed, in the 1980s, Camargue wetland sediments presented one of the highest lead shotgun pellet densities worldwide, approaching

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two million shotgun pellets per hectare at some sites (Pain, 1991). Given the long tradition of waterfowl hunting in the region (Mondain-Monval et al., 2009; Tamisier & Dehorter, 1999), it is likely that most hunting marshes still contain high pre-ban lead shotgun pellets which remain available as grit for waterbirds even 10 years after the ban. The rate at which lead shotgun pellets sink through soil and sediment and become less available to feeding waterfowl varies with soil conditions (Pain et al., 2015). Under certain conditions, shotgun pellets can remain available for decades. Kanstrup et al. (2020) showed that lead shotgun pellets persisted in Danish wetland sediments (0–20 cm depth) more than 33 years after strict enforcement of the law prohibiting their use. In the Camargue, Tavecchia et al. (2001) estimated the half-life of gunshot in the first 0–6 cm of sediments (available to waterfowl) to be 46 years, with complete settlement beyond this depth after 66 years.

Third, the prevalence and number of lead shotgun pellets ingested may remain high because of more recent inputs of lead shots in wetlands, caused by a lack of compliance with the ban on lead shells. The high proportion of lead shell cases found in the hunting areas surrounding the nature reserve of Tour du Valat indicates persistent use of lead shotgun shells by communal hunters in the Camargue, despite a slow increase in the use of nontoxic shotgun shells. This demonstrates that the effect of the ban did not reach the outcome that underpinned its implementation.

We show large differences in lead shotgun pellet contamination among waterfowl species. For the five species of Anatidae for which we have sufficient data (*Anas crecca*, *A. platyrhynchos*, *Mareca strepera*, *Mareca penelope* and *Spatula clypeata*), ingested lead pellet prevalence is similar to previous estimates in the Camargue since the 1960s (Allouche, 1983; Campredon, 1984; Pain, 1990; Pirot, 1978; Pirot & Taris, 1987), with the exception of Pain (1990), who obtained much higher values for *A. platyrhynchos* (47%) and *S. clypeata* (23%). The effects of family and diet we found confirm that lead consumption depends on species-specific behaviors, foraging strategies, and preferences for grit types (e.g., color; Moller & Erritzoe, 2010) where Anatidae and omnivorous species are more likely to pick up lead shotgun pellets.

Surprisingly, we did not detect any increase in nontoxic shotgun pellet prevalence and number in gizzards after the ban on the use of lead shotgun pellets, even though our monitoring of shell cases showed a slight increase in the proportion of steel shells used. Because nontoxic shotgun shells have been used by the hunters of the Tour du Valat since 1994 (Vallecillo et al., 2019), nontoxic shotgun pellets were already found in waterfowl gizzards before the lead ban (Mondain-Monval et al., 2015), which may explain the lack of a before–after ban effect.

Poor compliance with regulations banning the use of lead shotgun pellets for hunting waterfowl in England has been suggested to result from the ban being partial, that is only applied to waterfowl hunting (Stroud et al., 2021). We think this explanation also applies to explain the situation in France. Even in a country like France with a large and specialized body of civil servants (approximately 1700 environmental police staff) in charge of enforcing hunting and environmental laws, controls in the marshes are relatively rare. Furthermore, it is difficult to prove lead shotgun shell use by noncompliant hunters under current law. Indeed, hunters have to be caught with lead shells in the gun to be fined; it is still legal to carry lead shells around and in wetlands. In addition, when prosecution occurs, the relatively low amount of the fine (€135) is not a strong deterrent. Finally, skepticism regarding lead toxicity and misconceptions about nontoxic shells, suggesting that they are more expensive and generate more crippling loss than lead shells, remain common among hunters in the Camargue. These misconceptions remain despite documented comparability in price of similar shells and similar estimated levels of crippling losses (Kanstrup, 2019). Numerous efforts have been made in the Camargue to raise awareness among local hunters, including blind-test clay-pigeon shooting sessions with lead and nontoxic shotgun shells as well as numerous publications showing equivalent shooting effectiveness between lead and steel shotgun pellets at the recommended maximum shooting distance of 30 m (Ellis & Miller, 2022; Mondain-Monval et al., 2015; Mondain-Monval et al., 2017).

Poor hunter compliance affects birds other than game species. Lead contamination is a persistent threat for wildlife in the Camargue, probably affecting protected species such as Mute and Bewick swans *Cygnus olor* and *Cygnus columbianus*, and Common shelduck *Tadorna tadorna*. It may also affect raptors such as the Marsh harrier *Circus aeruginosus* and Bonelli's eagle *Aquila fasciata*. The risk may be particularly high for the Greater spotted eagle *Clanga clanga* (Vulnerable on both world and European Red lists) because its diet mostly consists of waterfowl in winter (Pérez-García et al., 2020). Finally, variations among European countries in the proportion of raptors found dead with high levels of lead in the liver indicated that only the complete ban on the use of lead shotgun shells in Denmark in 1996 was associated with a large reduction in lead contamination. No such reduction was evident in countries with partial bans on lead, particularly with bans in wetlands only (Green et al., 2022).

Although the Birds Directive (79/409/EEC and 2009/147/EC) does not mention lead shotgun shells specifically, it requires that hunting does not jeopardize conservation efforts of huntable species, and complies with wise use principles (Articles 4 & 7). Based on several

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established principles of public and international policy including the Birds Directive, Kanstrup et al. (2018) argued that the use of lead ammunition is not sustainable. In this respect, Commission Regulation (EU) 2021/57 of 25 January 2021 (European Union, 2021) contributes towards the full compliance with this Birds Directive by banning, starting 15 February 2023, the use of lead gunshot within wetlands or 100 m of wetlands, and also the carrying of lead gunshot while wetland shooting. This will hopefully contribute to solving these issues because the ban on 'carrying' should facilitate controls by environmental police and gamekeepers. Unfortunately, this new regulation has not yet (in 2025), been translated into a national decree allowing French wildlife service officers to act. While scientific efforts demonstrating the effect of pollutants on wildlife often stimulate the implementation of new policies, the monitoring of their effectiveness is rarely planned or funded although it can show compliance failure. For instance, such assessment showed the ineffectiveness of the enforcement of the ban on the veterinary use of diclofenac, which killed vultures, in India (Galligan et al., 2021).

Lead concentrations in the muscle tissue of wild-shot game are a good proxy for the ammunition type used to shoot them (Green et al., 2024). Pain et al. (2022) found that only the complete ban on lead shotgun shell used for all shooting (both in wetlands and in terrestrial habitats) in Denmark resulted in a substantial reduction in lead concentrations in game meat. Similar reductions do not appear to have occurred in countries with partial regulations (i.e., those covering only hunting in wetlands or of waterfowl, or voluntary bans; also see Gangoso et al., 2024). Consequently, it appears likely that a complete ban on all uses of lead gunshot will be needed to ensure high compliance in France, both within and outside wetlands. Such a complete ban on the use of all lead ammunition is currently under consideration across the EU as part of the EU REACH chemicals regulatory process. It would ensure human health protection regarding game meat consumption (Gerofke et al., 2018).

If accepted, this complete ban on lead ammunition would not come into force immediately. In the meantime, a coordinated international program should be initiated to monitor compliance with the recent, limited, ban in and around EU wetlands (European Union, 2021). Such monitoring should include the collection and analysis of representative samples of birds killed during hunting, along with systematic hunter checks, in each EU country. Effective interim monitoring would be a precursor to the more comprehensive monitoring needed if and when a complete ban on lead ammunition use for hunting is approved. A complete regulatory ban and an associated high compliance would be a major step towards ensuring more sustainable hunting practice across Europe (Kanstrup et al., 2018). This would better protect the health of game consumers, waterbirds, terrestrial birds and the environment.

AUTHOR CONTRIBUTIONS

Jean-Yves Mondain-Monval and Anthony Olivier conceived and designed the study. Gizzards collection were performed by Jean-Yves Mondain-Monval and Anthony Olivier, and the shell casings by Anthony Olivier. Gizzard analyses were performed by François Cavallo and Lou Sauvajon. Statistical analyses were performed by Arnaud Béchet and Pierre Defos Du Rau and discussed with all authors. The manuscript was written by Arnaud Béchet and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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DATA AVAILABILITY STATEMENT

Data used in this paper will be made available on Dryad (www.datadryad.org) after publication in Conservation Science and Practice.

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