Lead poisoning in wild birds from southern Spain: A comparative study of wetland areas and species affected, and trends over time

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Abstract

We studied lead (Pb) shot contamination in sediments from the Guadalquivir marshes and six other closed-basin lagoons in Southern Spain that are of major importance for threatened species of waterbirds. Shot densities were relatively low in Doñana, ranging from 0 to $25\,shot/m^2$ in the top 10 cm of sediments. The density at Medina lagoon (Ramsar site) was $148\,shot/m^2$, making it the most contaminated wetland known in Europe. Densities in the other five lagoons ranged from 9 to $59\,shot/m^2$. We studied the prevalence of ingested Pb shot in waterbirds from Doñana and found a lower prevalence in ducks than previously recorded in other Spanish wetlands. Lead shot were also found embedded in tissues of some waterbirds, proving that protected species such as the greater flamingo (*Phoenicopterus ruber*) and the glossy ibis (*Plegadis falcinellus*) are subjected to illegal hunting. The prevalence of embedded shot for geese was especially high (44% for trapped birds). Lead shot were detected in 2.8% of the pellets of the Spanish imperial eagle (*Aquila adalberti*) which usually preys on geese. We found that the prevalence of ingested Pb shot in geese and in Spanish imperial eagles has significantly decreased in recent years, possibly due to restrictions on hunting activity, efforts to remove shot from a sand dune used by geese to obtain grit, and to the high rainfall in Doñana during the last years that permitted waterfowl to stay more within the protected areas.
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1. Introduction

Wetlands in Andalusia (Southern Spain) are hugely important for migratory and sedentary waterbirds (Martí and del Moral, 2002, 2003) and are also important breeding areas for other birds such as raptors. The largest of these wetlands are the Guadalquivir Marshes (also known as Doñana, with a total area of 230,000 ha), but there are also several small lagoons of great interest for threatened waterfowl like the white headed duck (*Oxyura leucocephala*) and the crested coot (*Fulica cristata*) (Martí and del Moral, 2003). Doñana is one of the most important sites for wintering waterfowl in the Western Palearctic (Scott and Rose, 1996), with maximum counts of 82,000 greylag geese (*Anser anser*) in 1985 and 500,000 ducks in 1992 (Estación Biológica de Doñana, unpublished data).

This abundance of waterfowl has been exploited by hunters, leading to the spread of lead (Pb) shot pellets in these wetlands and consequent risk of Pb poisoning in birds (Mateo et al., 1998, 2000a, 2001a). In the Doñana National Park, several hunting techniques were used in the past, before the protection of the area and the ban of hunting in 1983. Geese were shot at several points where they concentrated in a predictable manner, especially at the Cerro de los Ánsares (goose hill), which is the largest sand dune in the Park. Hunting there from permanent blinds led to the accumulation of $16.2\,shot/m^2$ in the upper 20 cm of sand in 1997 (Mateo et al., 2000a). Ducks were hunted by following flocks on horseback with a large gun capable of shooting a particularly high number of pellets. The horse served as a support for the gun while shooting and also as a mobile hide. This type of hunting produced a more diffuse contamination of Pb shot in the marshes. As in other Spanish Mediterranean wetlands, ducks were also hunted from blinds around the deepest and most permanent areas

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(called "Lucios") of the Doñana marshes. However, previous studies of shot densities suggest that this type of hunting had a relatively low intensity in Doñana (Mateo et al., 1998).

Use of Pb shot for waterfowl hunting has been illegal in Andalusia since 2002, although it is unclear to what extent hunters have respected this ban. The Pb shot pellets accumulated in wetlands are ingested by waterfowl such as the greylag goose, causing prevalences around 10% and Pb poisoning to be a major cause of mortality in geese studied in Doñana before 2001 (Mateo et al., 1998). Other waterbirds have also previously been shown to be affected by Pb poisoning in Doñana: Pb poisoning killed 22 greater flamingos (Phoenicopterus ruber) in 1991 (Ramo et al., 1992), and Pb shot ingestion was recorded in 7.4% of purple gallinules (Porphyrio porphyrio) (Rodriguez and Hiraldo, 1975). The use of Pb shot for waterfowl hunting in Doñana also has an impact on raptors. Spanish imperial eagles (Aquila adalberti) and red kites (Milvus milvus) regularly ingest Pb shot embedded in the flesh of their prey (Mateo et al., 2001a), and high Pb bone levels ($>50\,\mu g/g$ d.w.) have been detected in Spanish imperial eagles (Pain et al., 2005).

Here, we present a study of Pb shot densities in some of the most important wetlands in Andalusia, both in and outside the Doñana area. We assess the prevalence of Pb shot in a range of waterbird and raptor species from Doñana, most of which have not previously been studied. Finally, we establish the trends of Pb shot ingestion in recent years for geese and raptors in Doñana, and consider how they are related to annual variation in the flooding pattern in the marshes and to the recent hunting restrictions.

2. Methods

2.1. Pb shot densities in sediments

Pb shot density was studied in various Andalusian wetlands between 2001 and 2003 (Fig. 1). Within the strictly protected Doñana National Park (54,252 ha) where hunting has been illegal since 1983, samples were taken at the Laguna de Santa Olalla (a permanent brackish lagoon) and Lucio de Marilópez (seasonal, brackish lagoon). Two areas where hunting still occurs were sampled in the neighboring Doñana Natural Park (53,835 ha): Lucio del Italiano in Veta la Palma (seasonal lagoon transformed into managed hunting ponds) and Salinas de Santa Teresa y San Carlos in Sanlúcar (four salt ponds dedicated to salt production, three of which have been abandoned). Four oxbows within the Brazo del Este Natural Area (1336 ha) were also sampled. Hunting was banned in the Brazo del Este (one of three original branches of the Guadalquivir River) in 1989, but illegal hunting continues there.

Outside the Doñana area, Pb shot were sampled in five complexes of closed-basin, semipermanent lagoons where waterfowl hunting was commonplace before their protection as Natural Reserves in 1987–1989. In Cádiz province we studied Salada de Zorrilla lagoon (19 ha) in the Espera complex, Salada (27 ha) and Chica (8 ha) lagoons in the Puerto de Santa María complex, Jeli lagoon (24 ha) from the Chiclana complex, and Medina lagoon (108 ha). We also studied Taraje lagoon (7.5 ha) in Seville province. Doñana National Park, Medina lagoon, and Salada de Puerto de Santa María lagoon are also protected as wetlands of international importance under the Ramsar Convention (Bernués, 1998). The other
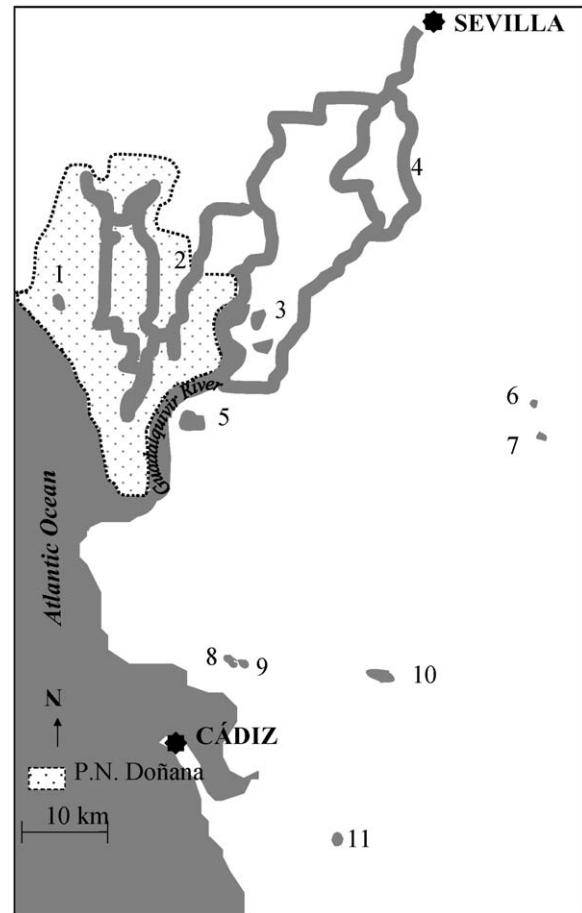

Fig 1. Map of the study area with sampling sites for Pb shot densities in sediments. 1, Santa Olalla; 2, Lucio de Marilópez; 3, Veta la Palma; 4, Brazo del Este; 5, Salinas de Sanlúcar; 6, Taraje de Sevilla; 7, Zorrilla de Espera; 8, Salada del Puerto; 9, Chica del Puerto; 10, Medina; 11, Jeli de Chiclana. P.N. Doñana = Doñana National Park.

wetlands studied are likely to be designated as Ramsar sites in the near future.

Sediment samples were collected from points spaced along transects with a PVC corer of 10 cm diameter for soft sediments or with a metal corer of 6 cm of diameter for harder ones. In the latter case, three subsamples were collected at each point to approach the same surface area sampled with the PVC corer, and densities were calculated as Pb shot pellets/m². Samples were taken by wading along transects from the bank toward the deepest central area. When information on the position of blinds used by hunters was available (Santa Olalla and Salinas de Sanlúcar), transects included the areas most likely to be contaminated by shot. The number of transects and samples collected on each varied between wetlands according to their surface area and depth profile (Table 1).

The depth of sediments sampled was 10 cm, and densities were studied for the 0–5 and 5–10 cm fractions separately. At Medina lagoon, which showed the highest Pb shot densities, an additional more detailed sampling was done to 30 cm depth to establish the viability of potential cleaning operations. When possible, sediment samples were sieved through a 1-mm mesh and Pb shot pellets were counted. The surface of shot pellets was scratched to confirm that they were Pb and not steel shot. After sieving, grit particles were retrieved, dried, and weighed in fractions of 1–2, 2–3, 3–4, and >4 mm diameter in 10% of the samples. Samples composed of clay that was difficult to sieve were studied by X-ray to establish the presence of Pb shot.

2.2. Ingested and embedded Pb shot in birds

Pb shot ingestion was studied in waterbirds and raptors from Doñana (see Tables 2 and 3 for sample size). Most waterbirds studied were found dead, but some greylag geese were trapped alive or collected to provide a less biased sample of Pb shot prevalence than for birds found dead. All these birds were studied by X-ray to detect ingested and embedded Pb shot. The gizzard of the birds found dead was examined to detect the

Table 1
Densities of Pb shot and availability of grit particles in the upper 10 cm of sediment in Andalusian wetlands

Zone	Sample (n)	Shot/m² mean[a]±SE	Mean grit availability (g/m²)				
			Size (mm)				
			1–2	2–3	3–4	>4	Total
Medina	201	148.3±12.2[A]	0	0	0	0	0
Salada del Puerto	80	58.9±14.0[B]	101.1	13.1	5.8	0	120±57
Zorrilla de Espera	92	26.7±7.0[BC]	9.6	4.0	4.7	0	18±8
Brazo del Este[b]	150	24.6±4.8[C]	3.5	1.2	9.2	8.2	22±22
Jeli de Chiclana	100	21.6±5.1[C]	0	0	0	0	0
Salinas de Sanlúcar[b]	115	18.3±4.4[C]	15.5	2.8	3.9	24.6	47±30
Chica del Puerto	21	12.1±8.4[C]	0	0	0	0	0
Santa Olalla[b]	130	11.8±3.2[C]	187.8	2.2	2.8	2.1	195±60
Taraje de Sevilla	30	8.5±5.9[C]	3.1	3.3	5.9	41.7	54±54
Lucio de Marilópez	15	0[C]	0	0	0	0	0
Veta la Palma[b]	60	0[C]	278.7	48.6	39.5	9.7	377±342

[a]Means sharing a superscript letter do not differ significantly (Mann–Whitney test, $P>0.01$).
[b]Wetlands within the Doñana marshes.

Table 2
Prevalence of Pb shot ingestion and embedded shot in waterbirds from Doñana

Species		Ingested shot		Embedded shot	
		N	With shot (%)	N	With shot (%)[a]
Greylag goose (*Anser anser*)	FD[b]	101	28 (27.7)[A]	49	32 (65.3)[A]
	T[c]	161	6 (3.7)*	45	20 (44.4)[ns]
Eurasian wigeon (*Anas penelope*)	FD	3	0	2	2
Gadwall (*Anas strepera*)	FD	38	0 (0)[B]	3	0
	T	4	0	4	1
Common teal (*Anas crecca*)	FD	48	0 (0)[B]	3	0
	T	1	0	1	0
Mallard (*Anas platyrhynchos*)	FD	128	8 (6.25)[B]	35	5 (14.2)[B]
	T	49	0 (0)[ns]	46	10 (21.7)[ns]
Northern pintail (*Anas acuta*)	FD	6	2	1	0
	T	9	0	9	3
Northern shoveler (*Anas clypeata*)	FD	72	3 (4.16)[B]	17	0 (0)[B]
	T	4		4	0
Marbled teal (*Marmaronetta angustirostris*)	FD	42	1 (2.38)[B]		
Red-crested pochard (*Netta rufina*)	FD	17	0 (0)		
Common pochard (*Aythya ferina*)	FD	22	1 (4.54)[AB]	2	0
	T	2	0	2	1
Ruddy duck (*Oxyura jamaicensis*)	T	5	1		
Greater flamingo (*Phoenicopterus ruber*)	FD	2	0	2	1
Glossy ibis (*Plegadis falcinellus*)	T	3	0	3	2
Purple gallinule (*Porphyrio porphyrio*)	FD	46	1 (2.17)[B]		
	T	23	0 (0)[ns]		
Eurasian coot (*Fulica atra*)	FD	155	2 (1.29)[B]	20	1 (5)[B]
	T	6	0	5	0

[a]Percentages sharing a superscript letter do not differ significantly (χ^2test, $P>0.01$), *Significantly higher percentage than in the trapped birds. ns: no differences between birds trapped and found dead. The marbled teal, flamingo, ibis, and gallinule are protected from hunting by national and European legislation.
[b]FD: found dead or moribund.
[c]T: trapped (shot or captured alive).

presence of ingested Pb shot. The uneroded pellets found in gizzards with shot entry holes were not considered as ingested. Those geese that were collected by shooting were harvested with No. 2 steel shot or bullets that can be easily recognized from the smaller Pb shot employed by hunters. The shot embedded in tissues represent a hazard for raptors feeding on waterfowl, and the frequency of Pb shot ingestion in these predators was evaluated by the analysis of their pellets by X-ray. The surface of the ingested shot pellets was scratched to confirm that they were Pb. Pellets were collected between 1997 and 2002 inclusive. Geese were collected or trapped between 1994 and 2004. Other waterbirds were collected between 1998 and 2001.

2.3. Data analysis

Densities of Pb shot pellets in sediments were compared among areas with a nonparametric Kruskal-Wallis test. Differences in Pb shot densities between depths of 0–5 and 5–10 cm were compared with a Wilcoxon's test for paired samples. The prevalences of embedded and ingested Pb shot (gizzards and pellets) were compared among species and by the method of collection with χ^2 or Fisher's exact tests, using those species with a minimum sample size of 20. Temporal changes in the presence of ingested Pb shot in greylag geese gizzards and Spanish imperial eagle pellets were tested with χ^2 tests. All tests were carried out using the SPSS 11.0.1 statistical package (SPSS, Chicago, IL).

3. Results

3.1. Pb shot densities in sediments

Densities in the upper 10 cm of sediment varied significantly among wetlands (Kruskal–Wallis test, $\chi_9^2 = 215.8$, $P < 0.001$), ranging from absence in Veta la Palma and Lucio de Marilópez to 148.3 shot/m^2 at Medina Lagoon (Table 1, Fig. 2). In Medina lagoon, the total density of Pb shot up to 30 cm of depth was 398.9 shot/m^2, with most shot concentrated between 5 and 20 cm depth (Fig. 3). In the other wetlands studied, the density of Pb shot was generally higher at 5–10 cm than at 0–5 cm (Fig. 2, Wilcoxon's test, $Z = 7.5$, $P < 0.001$). All the pellets found in sediments were Pb shot.

Grit availability differed among wetlands ($\chi_9^2 = 67.9$, $P < 0.001$), especially for grit of 1–2 and 2–3 mm diameter (Table 1). Grit was entirely absent in Medina Lagoon and other contaminated wetlands. Some other wetlands showed high densities of grit particles of size within the range of Pb shot numbers used for waterfowl hunting (1–4 mm).
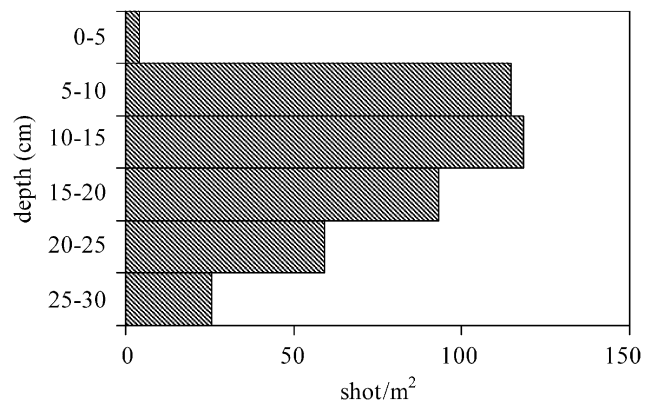
Table 3

Occurrence of Pb shot in pellets of raptors and carrion eaters from Doñana

Species	N	With Pb shot (%)[a]
Spanish imperial eagle (*Aquila adalberti*)	506	14 (2.8)[A]
Booted eagle (*Hieraetus pennatus*)	76	0[AB]
Red kite (*Milvus milvus*)	852	15 (1.8)[A]
Marsh harrier (*Circus aeruginosus*)	69	3 (4.3)[A]
Peregrine falcon (*Falco peregrinus*)	117	1 (0.9)[AB]
Barn owl (*Tyto alba*)	50	0[AB]
Eagle owl (*Bubo bubo*)	2	0
Raven (*Corvus corax*)	321	0[B]

[a]Percentages sharing a superscript letter do not differ significantly (χ^2 test, $P > 0.05$).

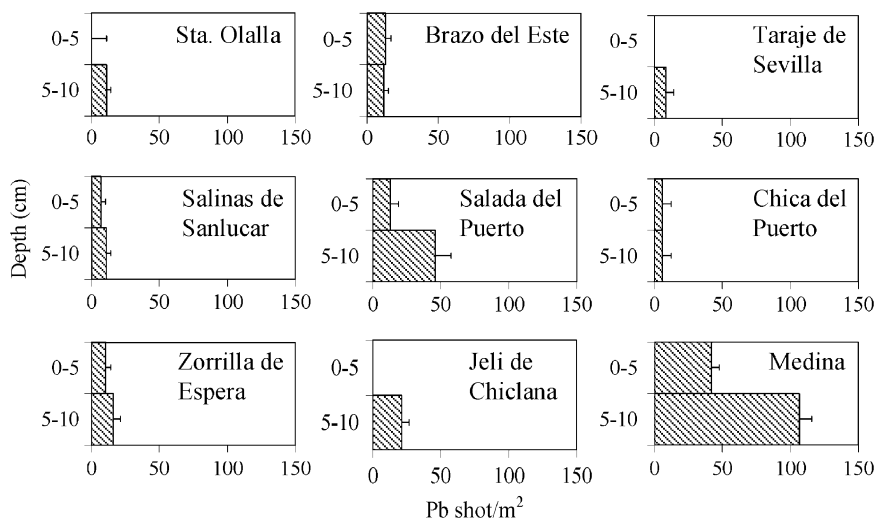Fig. 3. Distribution by depth of Pb shot densities (mean±SE) in sediments of the Medina Lagoon.

Fig 2. Lead shot densities (mean±SE) in sediments of the Guadalquivir Marshes (Doñana) and surrounding wetlands.

3.2. Pb shot ingestion in waterbirds

Pb shot ingestion was observed in nine species of waterbirds (seven Anatidae and two Rallidae), with differences among species in the prevalence of Pb shot ingestion (Table 2). All the pellets found in the gizzards were Pb shot. Sample size in several species was too small to give accurate prevalences of Pb shot ingestion. In the case of the birds found dead, greylag geese showed the highest prevalence of Pb shot ingestion. Greylag geese found dead also showed a significantly higher prevalence and number of Pb shot in their gizzard (27.7%; mean, 7.5; range, 1–47 shot) than geese captured by trapping or shooting (3.7%, $\chi^2 = 29.6$, $P < 0.001$; mean, 1.3; range, 1–2 shot). This difference was not observed in mallards (*Anas plathyrhynchos*) or purple gallinules. Prevalences obtained from birds found dead must be considered biased by the presence of a higher proportion of Pb poisoned birds. The prevalence of Pb shot ingestion in geese captured varied significantly among winters ($\chi^2_5 = 23.1$, $P < 0.001$), and Pb shot were only detected in the 1993–1994 and 1998–1999 winters (Fig. 4). Both these winters were prior to the ban of use of Pb shot for hunting and to a partial removal of Pb shot accumulated in Cerro de los Ánsares in 1999–2000. The overall prevalence detected in these two winters was higher (8.8%) than after the cleaning operations (0%, Fisher test, $P = 0.006$).

3.3. Embedded Pb shot in waterbirds

Embedded shot were recorded in six Anatidae and one Rallidae species, and also in greater flamingo and glossy ibis (*Plegadis falcinellus*) (Table 2). Embedded shot were recorded in similar proportions of greylag geese captured (44.4%) and found dead (65.3%, χ^2 test, $P = 0.07$), and at a higher level in geese than in the rest of the species (Table 2).
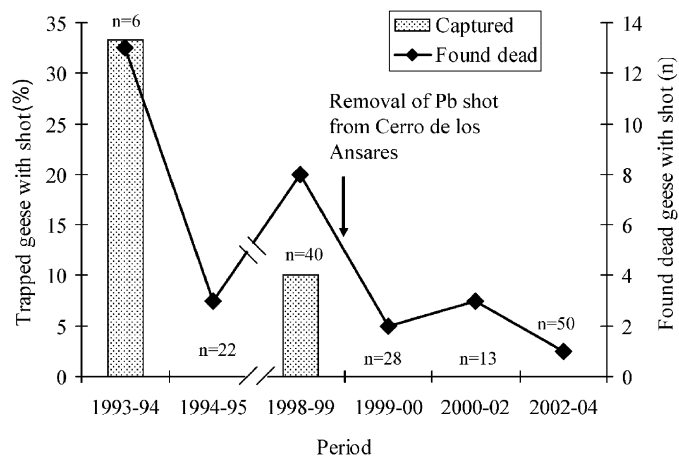

Fig. 4. Temporal changes in the prevalence of Pb shot ingestion and registered cases of Pb poisoning in greylag geese wintering in Doñana during the last decade.
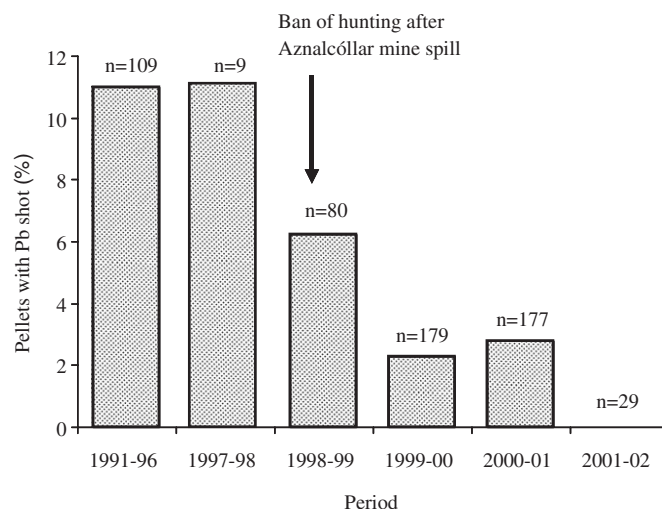

Fig. 5. Occurrence of Pb shot in pellets of Spanish imperial eagle collected in Doñana during the last decade. The data of the first bar correspond to the study of Mateo et al. (2001). The difference between periods is significant ($\chi^2_5 = 14.5$, $P < 0.001$). Waterfowl hunting was banned after the Aznalcóllar mine spill on April 1998 until January 1999.

3.4. Pb shot ingestion in birds of prey

Pb shot ingestion was confirmed in pellets of four species of raptors with prevalences ranging from 0.9% to 4.3% (Table 3). Three of the four species containing Pb shot in their pellets are species with opportunistic scavenging habits: Spanish imperial eagle, red kite, and marsh harrier. No differences in the occurrence of Pb shot were observed between the pellets of Spanish imperial eagle collected during the hunting season (October–February; $n = 115$, 1.7% with Pb shot) and the rest of the year ($n = 350$, 2.9%; χ^2 test, $P = 0.7$).

The occurrence of Pb shot in the pellets of the Spanish imperial eagle showed a decrease in time (Fig. 5). If we compare the years before and after 1998, when hunting was temporarily banned for public health protection following a spill of mining waste, the occurrence of Pb shot in pellets declined from 11% to 3% ($\chi^2 = 11.9$, $P < 0.001$, Fig. 5).

4. Discussion

In the upper 10 cm of sediment, Pb shot densities in most of the Andalusian wetlands studied here are within the range of 22.5–85.7 shot/m^2 observed previously in other wetlands on the Spanish Mediterranean coast (Mateo et al., 1997, 1998). However, the density observed in Medina Lagoon (148.3 shot/m^2) is, to our knowledge, the highest recorded in Spain and one of the highest observed in wetlands anywhere due to waterfowl hunting practice. Rocke et al. (1997) observed 214.2 shot/m^2 at the same depth in Sacramento National Wildlife Refuge in California. In the upper 20 cm of sediment, Medina lagoon also has a higher Pb shot concentration (330.5 shot/m^2) than the Spanish wetlands studied previously (6–287.5 shot/m^2; Guitart et al., 1994; Mateo et al., 1997, 1998) and than

other Mediterranean wetlands such as the Camargue in France (199.5 shot/m^2; Pain, 1991).

The high presence of Pb shot in the Medina lagoon seems especially problematic because it is accompanied by the absence of grit of an appropriate size (>1 mm of diameter) for most of the waterfowl species (Pain, 1990; Mateo et al., 2000b, 2001b). Experimental and field studies show that ducks mainly ingest shot confounded as grit (Moore et al., 1998; Mateo and Guitart, 2000). This wetland is particularly important for the globally threatened white headed duck (Torres and Moreno–Arroyo, 2000) and Pb poisoning has been shown to be a significant cause of mortality for this species in other Spanish wetlands (Mateo et al., 2001b). Future studies are needed to assess the prevalence of Pb shot in waterbirds using Medina lagoon. The tillage of contaminated sediments to reduce Pb shot availability for birds has been studied as an alleviating measure in other areas (Fredrickson et al., 1977; Peters and Afton, 1993; Thomas et al., 2001). However, this option is not viable at Medina given the presence of shot in deeper layers of sediment at even higher concentrations than at the surface. Under these circumstances, tillage is likely to increase Pb shot availability for birds as occurred in Encanyissada lagoon in the Ebro delta in Northeastern Spain (Mateo et al., 1997). We are not aware of specific studies of the depth in sediments to which waterbirds feed, but ducks, flamingos, and other waterbirds feed extensively on invertebrates and seeds within the sediments, and are likely to feed to a depth at least equivalent to their bill length (3.5–5.5 cm in the case of *Anas* ducks; Cramp and Simmons, 1977). Flamingos are common at Medina and the other wetlands we studied, and create craters in soft sediments by treading with their feet when feeding (Rodríguez-Pérez and Green, 2006). When excavating these craters, flamingos are likely to unearth Pb shot at depths exceeding 5 and perhaps 10 cm.

Prevalences of Pb shot ingestion observed here for ducks from Doñana are lower than in Spanish wetlands studied previously, where prevalences in granivorous wintering ducks such as mallard or common pochard varied between 22% and 87% of individuals shot by hunters (Guitart et al., 1994; Mateo et al. 1998, 2000b). The prevalences we recorded are also lower than those for the Camargue in France (9–36% for granivorous ducks; Pain, 1990; Mondain-Monval et al., 2002). In a previous study carried out in Doñana, the prevalence of Pb shot ingestion in greylag geese shot by hunters was 10% compared with 27% observed in those found dead (Mateo et al., 1998). As most of the ducks we studied here were found dead, the real prevalence of Pb poisoning in ducks from Doñana must clearly be lower than in other European wetlands on the Mediterranean coast. This general difference can be explained by the relatively low intensity of hunting activity in Doñana in recent decades. Hunting has been banned in a progressively larger proportion of the Guadalquivir Marshes since the declaration of the Doñana National Park in 1969. Even before then, hunting in what is now the National Park was largely reserved for a few rich land owners (Fernández, 1990).

The greylag goose remains the main quarry of hunters in the Doñana marshes, which hold most of the wintering population in Spain (Martí and del Moral, 2002). The overall prevalence in the greylag goose is not too dissimilar to the values observed for other *Anser* species in Texas (4.3%), where the prevalences in ducks were quite high (12% in mallards and 29.5% in other *Anas* species; Sanderson and Bellrose, 1986). Despite the relatively low prevalence of shot ingestion in geese collected in Doñana, Pb poisoned geese were found throughout the study period.

The presence of embedded Pb shot in waterfowl is the main cause of Pb poisoning for raptors in wetlands (Patte and Hennes, 1983). The high prevalence of embedded Pb shot in waterbirds captured and found dead in the Guadalquivir Marshes indicated a risk of Pb shot ingestion by raptors feeding on them. The pellets of Spanish imperial eagles and red kites from Doñana containing bird remains had Pb shot more frequently than those with mammal remains (Mateo et al., 2001a). The percentage of captured birds with embedded shot is especially high in the greylag goose (44.4%), indicating a high hunting pressure of this species along its migratory flyway. This percentage is comparable with values reviewed by Scheuhammer and Norris (1996) ranging from 10% to 68% for several waterfowl species. The presence of Pb shot in pellets of marsh harriers recorded by us in 2001–2002 (4.3%) was higher than that recorded in 1982–1984 (1.8%; González, 1991), but lower than in other wetlands in Southern Europe (11–17%; Pain et al., 1993, 1997; Mateo et al., 1999). We collected the marsh harrier pellets from the Brazo del Este, that part of the Doñana marshes where illegal hunting activity is most intense. The presence of embedded shot in two of three glossy ibis is probably explained by the concentration of this protected species in the Brazo del Este during the winter period. Embedded shot were also recorded in the flamingo, which is considered a pest in the rice fields in Doñana as in the Camargue (Tourenq et al., 2001).

The declining trends of Pb shot ingestion in greylag geese and Spanish imperial eagles in Doñana are probably related to recent reductions in the availability of Pb shot for several reasons. In the case of the goose, this may result from a partial cleanup of Cerro de los Ánsares in the summers of 1999 and 2000 (Dávila and Domínguez, 1999), when about 100 kg of Pb shot were manually removed from the surface layer of this major site of grit ingestion for geese from all over Doñana. In 1997, the Cerro de los Ánsares contained 26.1 kg of Pb shot/ha in the upper 20 cm of this sand dune that has a surface of 150 ha (Mateo et al., 2000a). Although similar data are not available after the cleanup operations, the amount of Pb removed may have been significant. Geese themselves may also have contributed to the decontamination of the dune to a lower extent. Pb shot ingestion could be estimated at 5.5 kg/year from an assumption of 10% prevalence of one ingested

shot per bird in 60,000 geese wintering for 5 months in Doñana. Annual variations of Pb shot on the surface may be expected due to the movement of this mobile dune. Moreover, Pb shot was banned for waterfowl hunting in Andalusian wetlands since 2002, although no information exists about the compliance by hunters. In the United States, where this compliance was high (Havera et al., 1994), the decline in prevalence of Pb shot ingestion was significant in several species within a few years (Moore et al., 1998; Anderson et al., 2000).

In the case of Spanish imperial eagles, the ban of waterfowl hunting for public health reasons after the spill of pyrite waste from the Aznalcóllar mine on April 1998 (Grimalt et al., 1999) until January 1999 may have reduced the availability of goose carcasses with embedded Pb shot for this raptor during the season 1998–1999. Although the presence of Pb shot in pellets of Spanish imperial eagle in Doñana was found to be higher during the hunting season in a previous study (Mateo et al., 2001a), this difference was not detected for the period 1997–2001 and this may be due to a reduced hunting pressure on geese. Furthermore, the recent years with lower Pb shot ingestion by geese and eagles had high rainfall, and geese spent more time within the flooded temporary marshes of the National Park where hunting is banned, and less time in surrounding rice fields and other areas where hunting is permitted (Fig. 6). Consequently, the observed trends may be partially due to a lower risk of geese ingesting Pb shot and being shot in the latter areas.

In the future, we need to study prevalences of Pb shot ingestion in waterbirds in Medina Lagoon, especially because of the implications for conservation of threatened species. Densities of Pb shot in Cerro de los Ánsares should also be reinvestigated to determine if Pb shot should be removed from other parts of the dune. Finally, the presence of Pb shot in the pellets of the Spanish imperial eagle in Doñana should be monitored to assess the long-term effect of the ban of Pb shot for waterfowl hunting. Although the

decline of the Pb exposure after this ban is expected to be more immediate in raptors than in waterfowl (since only waterfowl ingest Pb shot deposited in sediments years before), previous experiences have demonstrated that local restrictions may not be effective for raptor conservation (Kramer and Redig, 1997). Since most of the geese and ducks wintering in Doñana migrate through France (where there are currently no restrictions on the use of Pb shot), raptors in Doñana may continue to ingest embedded Pb shot.
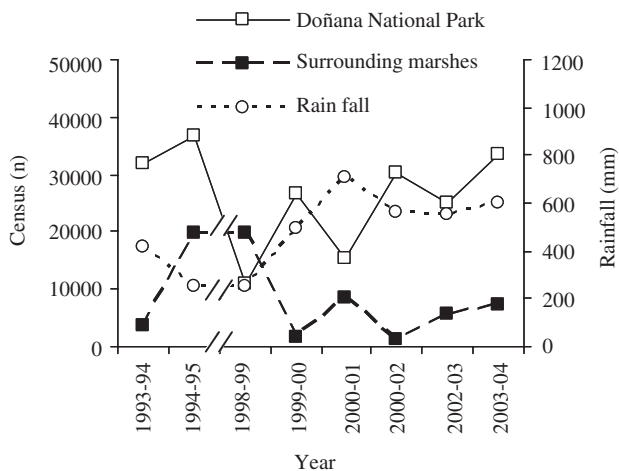
Acknowledgments

Fig. 6. Mean census of Greylag geese wintering between November and February in Doñana National Park and the surrounding areas of the Guadalquivir Marshes are shown with the annual rainfall in the area.

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