



Crippling rates of waterfowl by gunshot in Northwestern Europe: interspecific and geographic differences give clues to possible management challenges and options

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Abstract

Waterbird hunting is to be performed sustainably with respect to conservation status and animal welfare. Birds that are hit but not killed by shotgun pellets suffer what is called crippling. Here, we present data on crippling rates, i.e., the proportion of x-rayed birds with embedded shotgun pellets, of x-rayed individuals of nine waterfowl species in six European countries during 2017–2022. We x-rayed 3,843 individuals, of which 17% had been crippled. Logistic regression models showed that the risk of crippling varied between species, and increased with age, but not with individual body mass within species. On average, crippling rates increased with the average body mass of the species; the highest crippling rate was detected in bewick's swans and greylag geese, with respectively 33% and 28% of individuals being crippled, and the lowest rate in Eurasian wigeons and brent geese, with respectively 5% and 4% being crippled. On average 19% of adult birds carried embedded pellets, versus 4% of first year birds. The higher crippling rates and embedded pellet numbers in adults than juveniles suggested cumulative exposure. Crippling rates of geese differed between countries and with population status, as exemplified by barnacle goose; 15% of wintering adults were crippled in The Netherlands versus 9% in Germany, and 15% of adults of winter migrants versus 21% of an intensively managed sedentary population in The Netherlands. The reported crippling rates are within the range of previously reported crippling rates of geese and swans, including high rates for bewick's swan and barnacle goose that are protected in part of their range. The analysis identifies that crippling continues to be a conservation and animal welfare concern that can be tackled effectively via targeted management actions.

Keywords Crippling · Gunshot pellets · Waterbirds · Europe · Flyway management · X-ray

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Introduction

During bird hunting there is an inherent risk that shotgun pellets penetrate the skin with non-lethal effects, so called “crippling” and these ammunition remains may be embedded in the tissue of the birds. Crippling levels of populations are usually reported as a “crippling rate”, defined as the proportion of birds with embedded shotgun pellets. Typically, crippling rates can be determined by x-raying birds (alive or carcasses), where the shotgun pellets are easily identified and counted, and pellets present in the gizzard (ingested) can be separated.

Crippling constitutes not only an ethical and animal-welfare problem but may also potentially affect waterbird population dynamics as embedded pellets may lower survival rates (Madsen and Noer 1996; Tavecchia et al. 2001; Guillemain et al. 2007). Crippling risk can be affected by shooting distance, weather conditions, hunters’ experience and the type of ammunition (Noer et al. 2007). For example, with increasing shooting distance to target, shotgun pellet dispersion increase and velocity of projectiles decrease, with following increasing risk of crippling of birds (Van Dyke 1981; Noer et al. 2007).

Crippling rate is expected to be related to population off-take rate, i.e., the proportion of individuals being killed by either hunting, lethal scaring or derogation shooting (Clausen et al. 2017). Derogation shooting, i.e., the shooting of protected waterbirds authorized under derogation permits from the EU Birds Directive in order to prevent serious damage to agriculture or ensure flight safety, has increased considerably during the past decades (Fox et al. 2017). In Europe, particularly the populations of greylag goose (*Anser anser*), greater white-fronted goose (*Anser albifrons*) and barnacle goose (*Branta leucopsis*) have increased rapidly during the last decades causing conservation-agricultural conflicts. This has led to increasing stakeholder demands to decrease goose numbers resulting in increased hunting and derogation shooting (Fox and Madsen 2017; Koffijberg et al. 2017; Madsen et al. 2017; Liljebäck et al. 2021; Jensen et al. 2022). With increasing shooting there is a growing concern over the negative side effects such as an increase in crippling (Noer and Madsen 1996; Tavecchia et al. 2001; Noer et al. 2007).

Monitoring of crippling is now part of goose management in Europe to inform decision makers about possible negative aspects of hunting (Madsen and Williams 2012; Marjakangas et al. 2015; Jensen et al. 2018; Powolny et al. 2018; Månsson et al. 2024). Continued reduction of crippling rates is part of the management and conservation objectives, and changing hunters’ shooting practices to reduce crippling are a key action to achieve this. Being an ethical issue related to hunters’ performance, minimizing

crippling is necessary to sustain acceptance of hunting, e.g. to control population numbers, in the agreed management plans (Madsen et al. 2015).

In order to document the current crippling rates we here present data of nine waterfowl species collected by x-raying in 2017–2022 in six countries in northern Europe. We compare crippling rates across species and countries, and evaluate relationships between crippling rates and age, sex, individual body mass, population (migratory or sedentary) and legal status of the various waterfowl species. We expected higher crippling rates in species that are subject to high intensity of shooting, such as greylag goose, and lower crippling in smaller, less intensely targeted species such as Eurasian wigeon (*Mareca penelope*). Larger species could also generally be more easily hit, survive crippling better and live longer (Speakman 2005), and are therefore likely to suffer higher risk of crippling over the course of their lives. For the same reason, we expect body mass of individual waterfowl and their crippling rate and the number of pellets to be positively related. We also expect higher crippling rates in countries such as The Netherlands with more derogation shooting compared to e.g. Germany with more strict policy, and examined this in detail for barnacle goose, for which we sampled individuals in three countries (The Netherlands, Germany and Denmark). As derogation shooting is frequent and is likely to impact sedentary populations more than migratory ones, we expected barnacle geese caught in summer to have higher crippling rates than the mix of largely migratory and some sedentary geese present in winter. We further expect more crippling in adults than in juveniles because of pellet accumulation during life; and in males than females due to the lower body mass of the latter. Finally, we present cases by which data can decipher national challenges, which offers more tailored management options to reduce the problem.

Materials and methods

X-raying of waterbirds was performed as part of ringing procedures (e.g., Månsson et al. 2022; Moonen et al. 2023), and during culling operations of geese performed as part of the population management in The Netherlands. During ringing procedures, geese, ducks and swans were caught using traditional clap-nets and cannon-nets during winter, or by corralling them into nets during their moult in The Netherlands, Lithuania, Denmark, Norway, Sweden, and Germany, between May 2017 and July 2022 (Appendix 1). During culling operations, greylag geese were also x-rayed immediately after being killed during culling operations performed as part of a population reduction scheme in The Netherlands. After corralling them during moult into

a standing fence, the geese were transferred into a closed trailer in which they are rapidly killed using CO₂ gas. Digital radiography, i.e. radiography that uses x-ray sensitive digital plates, to capture images of the examined bird was used to determine crippling by ocular examination. We used the mobile x-ray system ACOMA PX-15HF, with the digital plate model Mars1417V-TSI from iRay Technology. In Sweden, birds were also x-rayed using a VIVIX-S 1417 N detector combined with a portable Econet Vet20BT x-ray unit, and a Sedecal SP-VET-4.0 with Beam device r 72/170A DHHS. As part of the ringing procedure, waterbirds were wrapped in a dark cotton bag to keep them calm whilst being x-rayed in the field with an x-ray generator and a detection plate. Shotgun pellets were easily identified in the images. Multiple x-rays were taken if needed i.e. if the first picture missed out parts of the bird. Cases where pellets resided in the gizzard, i.e. were ingested and not inflicted, were excluded (Noer and Madsen 1996). Ageing and sexing of the birds was based on plumage characteristics and cloacal examination. Two age classes were discriminated, juvenile (i.e. in the first year of their life) and older birds. Body mass (g) was obtained by weighing the x-rayed birds.

Crippling rate was defined as the proportion of x-rayed birds with at least one embedded shotgun pellet. We assessed crippling rates by species, country, season (summer and winter), age and sex for those species where sample size was adequate. To determine what sample size was adequate, the observational error in the crippling rate can be thought of as the margin of error (MOE), and the sample size needed to require a certain MOE, for instance with a 95% confidence interval MOE₉₅, can be approximated. When assuming a given crippling rate (p), then: $MOE_{95} = 1.96 * \sqrt{((p(1-p)/n))}$, with any given n equal to $n = 1.96^2 * (((p(1-p)/MOE_{95}^2))$. Because previously reported crippling rates of waterfowl varied between 14 and 62% (e.g., Grieb 1970; Norman 1976; Anderson and Sanderson 1979; Humburg et al. 1982; Noer and Madsen 1996; Holm and Madsen 2013; Newth et al. 2019), we assumed a minimum crippling rate of 14%. A margin of error of 10% (with 95% confidence) could thus be obtained with a sample size of: $n = 1.96^2 * (((0.14(1-0.14)/0.1^2)) = 46$ birds.

Comparisons of crippling rates between species, populations (migratory or sedentary) and countries were conducted with all birds and only adult birds, as we expected that juveniles had a lower proportion of crippling, which complicates comparisons if samples included a different proportion of juveniles. For barnacle goose, we compared birds caught during summer (June, July) in The Netherlands and geese caught during winter (all other months). Adult summer geese from The Netherlands are mainly sedentary birds, i.e., most stay in The Netherlands year-round. Barnacle geese caught during winter consists of a mixture between migratory and

non-migratory birds from countries along the flyway (Van Der Jeugd et al. 2009), with migratory geese usually greatly outnumbering non-migratory geese. For greylag geese, we compared summer catches (May, June) in The Netherlands versus those in Sweden; Dutch birds are mainly sedentary (Voslamber et al. 2010), whereas Swedish greylag geese are largely migratory (Månsson et al. 2022). Eurasian wigeons were sampled in The Netherlands in autumn (Oct-Nov) and spring (Feb-Mar). During these periods, birds would either be migrating to the U.K. and France (in autumn, the middle of the hunting season), or would have just arrived from their wintering grounds in those countries (spring, the end of the hunting season).

Statistics

We used both generalized linear models and generalized linear mixed models implemented in the stats package and lmer4 package in R studio v. 3.0.3.1. (R Development Core Team, 2023) to model how explanatory variables affected crippling and the number of pellets in case of crippling. In the first set of generalized linear mixed models with a binomial distribution and logit link function, we examined the relative support for alternative hypotheses: that crippling (yes=1, no=0) of European waterfowl is best explained by the species, the body mass of individual birds, their sex, or age (juvenile/adult). Age, sex, and species were included as categorical variables. Body mass was included as a factor nested within species, which ensures that the influence of body mass is measured within species and not between species. In another set of generalized linear models, we examined for barnacle geese how their crippling was affected by the country where they were examined (The Netherlands, Germany, and Denmark), their body mass, age, and sex; and, separately for barnacle geese x-rayed in The Netherlands, how season of examination (winter or summer) representing their population status (respectively, largely migratory, or sedentary), and body mass, age, and sex affected their crippling. Finally, we examined how the number of embedded pellets in crippled waterfowl in Europe was affected by body mass (nested within species), age, species, and sex, using a generalized linear mixed models with a Poisson distribution and logit link function.

We explored models consisting of all possible subsets of combinations of explanatory variables and used the corrected Akaike information criterion (AICc) value to select the most parsimonious models (the best approximating model, with the fewest parameters, given the data, i.e. with the lowest AICc; Burnham and Anderson, 2002), and the top two $\Delta AICc$ of models as the cut-off criterion for delineating a set of top models. We excluded here more complex models than the best models within $\Delta AICc < 2$ units, as more

Table 1 The proportion of the total number of x-rayed waterfowl with embedded shotgun pellets (i.e., crippling rate) in Denmark, Germany, The Netherlands, Lithuania, Norway, and Sweden 2017–2022. the average body mass of the individuals in the sample is indicated

Species	Number of x-rayed individuals	With pellets (%)	Body mass (g)
Bewick's swan	46	33	5751
Canada goose	106	14	3898
Greylag goose	788	28	3338
Pink-footed goose	465	15	3077
Bean goose	76	14	2833
Greater white-fronted goose	71	13	1984
Barnacle goose	1668	16	1814
Dark-bellied brent goose*	350	4	1610
Eurasian wigeon	273	5	739

*includes 1 Light-bellied Brent goose

Table 2 The proportion of total number of x-rayed waterbirds with embedded shotgun pellets (i.e., crippling rates) by age group in Denmark, Germany, The Netherlands, Norway, and Sweden, in 2017–2022

Species	Adults (%)	<i>N</i>	Juvs (%)	<i>N</i>
Total 9 species	19	3245	4	525
Barnacle goose	17	1453	5	155
Dark-bellied brent goose	6	265	0	84
Pink-footed goose	20	322	6	143
Eurasian wigeon	6	214	6	53

complex models include uninformative variables that do not explain enough variation to justify their inclusion (Arnold 2010). We computed model-averaged parameters by averaging over the models in the set of top models. We used the dredge function in R (part of the package MuMIn v. 1.9.5; Bartoń 2013) to implement a model-averaging approach for the top models to make robust parameter estimates and predictions (Johnson and Omland 2004), and estimated the relative importance of each variable, based on the sum of Akaike weights. We subsequently evaluated the effect of variables based on overlap of the 95% confidence intervals (Burnham and Anderson 2002).

Results

Crippling rate by species, body mass, age and sex

In total, we x-rayed 3,843 individuals of 9 species (Table 1). Overall, 17% of the birds examined carried embedded pellets. On average, crippling rates increased with the average body mass of the species (Table 1); the highest crippling rate was detected in bewick's swans (*Cygnus columbianus bewickii*) and greylag geese, with respectively 33% and 28% of individuals being crippled, and the lowest rate in Eurasian wigeons and dark-bellied brent geese (*Branta b. bernicla*), with respectively 5% and 4% being crippled.

Table 3 Generalized linear models with a binomial distribution and a logit link function examining the relationship between crippling (C ; 1 = crippled or 0 = not crippled) and age (A), County ($Cntr$), species (Sp) and sex (S) of 9 species of waterfowl in Europe, with number of parameters (k), corrected Akaike information criterion (AICc), Δ AICc and Akaike weight. Table includes only the top model (lowest AICc) and the null (constant) model, as the other candidate models all have an Δ AICc greater than two units of the top model

Model	<i>k</i>	AICc	Δ AICc	<i>w</i>
$C \sim A + Sp$	11	2855.5	0.00	0.53
$C \sim constant$	2	2738.4	149.91	0.00

Generally, for pooled data including all 9 species (Table 2), crippling rates were higher for adult birds (19%) compared to juvenile birds (4%). The Eurasian wigeon was the only species that showed similar crippling rates for both age groups, 6% of adults and juveniles. There was no general difference in the crippling rates between sexes; for 9 species combined, 15% of 1554 females and 15% of 1760 males were crippled.

Our models found strong support for species and age affecting crippling, which were included in the most plausible model (i.e. model with Δ AICc ≤ 2 ; Table 3). Sex and body mass nested in species had no effect on crippling and were excluded from the models. The single top model (Table 4) showed that adults were more often crippled than juveniles, and that bewick's swan and greylag goose were more crippled than barnacle goose, whereas Eurasian wigeon, and dark-bellied brent goose were less crippled (Fig. 1).

Crippling rate by country and population status

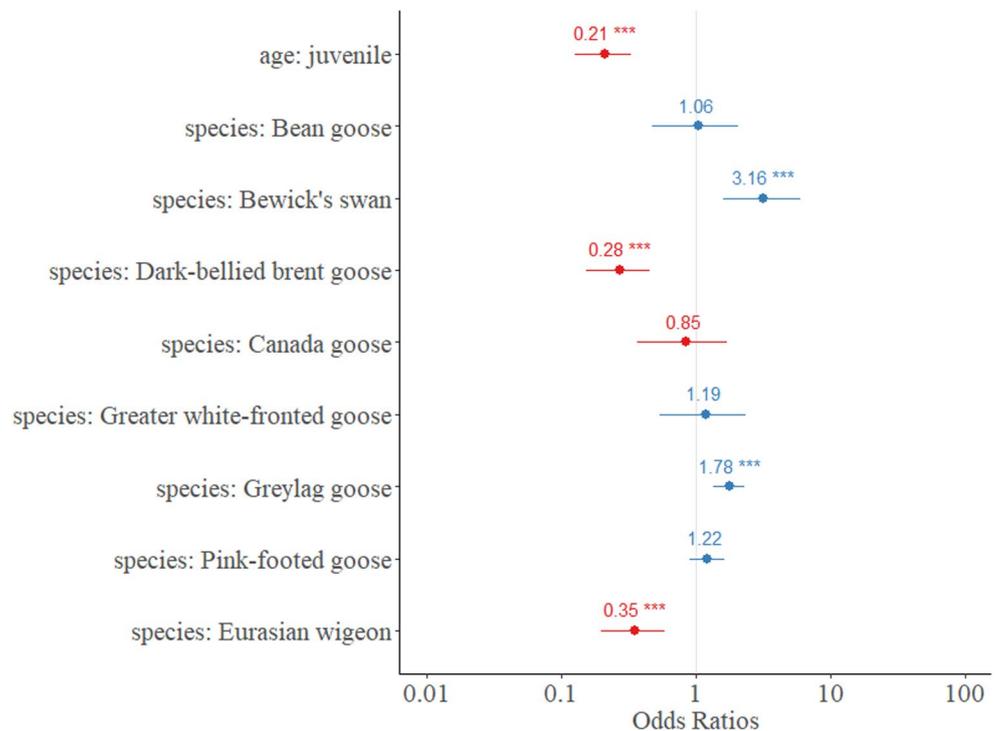
The sample sizes were in most cases sufficient for a reliable assessment of crippling rate per species and country, with a few exceptions when only adults were considered (Table 5). There was substantial variation in the crippling rate between countries for barnacle geese during winter, with 15% of adults in The Netherlands carrying pellets versus 9% of adults in Germany. The crippling rates differed between seasons in The Netherlands; 15% of adult barnacle geese caught in winter were crippled versus 21% of adults caught in summer. The only other species measured in more than one country, the greylag goose, had adult crippling rates of 22% and 30% in Sweden and The Netherlands, respectively, during summer. Crippling rates in adult Eurasian wigeon were comparable between autumn (4%) and spring (8%) catches, corresponding to open hunting season and post hunting, respectively.

We found strong support for the effect of age and country on crippling of barnacle geese in Germany, The Netherlands and Denmark, which were both included in the top three models with Δ AIC ≤ 2 (Table 6). The top model (Table 7) supported the hypothesis that barnacle geese were more

Table 4 Effects of age (*A*) and species (*Sp*) assumed to influence crippling of 9 waterfowl species in Europe. Age reference group: adult. Species reference group: barnacle Goose

Variable	Estimate (β) ^a	Conditional \widehat{SE}_{β}	Z value	2.5% – 97.5%	Effect ^b
<i>Constant</i>	-1.60	0.07	-22.46	-1.73 to -1.46	***
<i>A_{juvenile}</i>	-1.55	0.24	-6.47	-2.05 to -1.11	***
<i>Sp_{Bean goose}</i>	0.06	0.37	0.15	-0.74 to 0.74	
<i>Sp_{Bewick's swan}</i>	1.15	0.33	3.46	0.47 to 1.79	***
<i>Sp_{Dark-bellied brent goose}</i>	-1.29	0.27	-4.70	-1.87 to -0.79	***
<i>Sp_{Canada goose}</i>	-0.16	0.39	-0.41	-0.99 to 0.55	
<i>Sp_{Greater white-fronted goose}</i>	0.17	0.37	0.47	-0.62 to 0.86	
<i>Sp_{Greylag goose}</i>	0.58	0.14	4.27	0.31 to 0.84	***
<i>Sp_{Pink-footed goose}</i>	0.20	0.15	1.32	-0.10 to 0.49	
<i>Sp_{Eurasian wigeon}</i>	-1.04	0.28	-3.78	-1.63 to -0.54	***

Fig. 1 Odds ratios resulting from the top model of generalized linear model with a binomial distribution and a logit link function, testing the effect of age and species on crippling (1 = crippled or 0 = not crippled) of 9 waterfowl species in Europe. Age reference group: adult. Species reference group: barnacle goose



often crippled when adult than juvenile, and when x-rayed in The Netherlands compared to Germany, but at similar rates in The Netherlands and Denmark (Fig. 2a). Furthermore, model averaging showed that crippling of barnacle geese in the Netherlands was strongly affected by the population status of the geese and age, which featured in all three top models (Table 8), with higher odds of crippling in sedentary geese compared to largely migratory individuals, and lower odds in juveniles compared to adults (Table 9, Fig. 2b). Sex was included in the top model set but did not have a significant effect.

Shotgun pellet numbers

The majority of individuals had single embedded pellet, but the maximum recorded was 28 pellets in an individual greylag goose (Fig. 3).

The top model examining how the variation in the number of embedded pellets in crippled waterfowl in Europe was best explained, included age, sex and species, of which age and sex were also included in the second best model (Table 10). Adding body mass nested within species did not improve the model, suggesting it had no ecological value.

Table 5 The proportion of the total number of x-rayed waterbirds with embedded shotgun pellets (i.e., crippling rate) by country in 2017–2022. The number of x-rayed individuals and adults only are presented, and the proportion of birds with one or more pellets, for all birds and adults only. The months of the x-ray monitoring, and the migration status of the majority of individuals (M= migratory, R= resident) are also presented. Asterisks indicate cripple rates based on low sample size (i.e. < 46 individuals)

Country	Species	Number of x-rayed individuals	Number of x-rayed adults	% with pellets	% adults with pellets	Months	Status
Denmark	Barnacle goose	50	26	18	19*	March	M
Germany	Barnacle goose	269	213	8	9	March, April	M
The Netherlands	Barnacle goose	534	470	13	15	Jan, Feb, Mar, May, Nov, Dec	M
	Barnacle goose	795	729	21	21	June, July	R
	Bean goose	76	45	14	20*	Feb, Oct, Dec	M
	Bewick’s swan	46	35	33	43*	January	M
	Dark-bellied brent goose	350	266	4	6	Mar, May, Nov	M
	Canada goose	94	89	12	12	June	R
	Greater white-fronted goose	52	33	13	21*	Jan, Feb, Oct, Nov, Dec	M
	Greylag goose	622	622	30	30	May, June	R
	Eurasian wigeon	176	138	5	4	Oct, Nov	M
	Eurasian wigeon	97	76	6	8	Feb, Mar	M
Norway	Pink-footed goose	465	322	15	20	May	M
Sweden	Greylag goose	139	134	22	22	June	M

Table 6 Generalized linear models with a binomial distribution and a logit link function examining the relationship between crippling (C ; 1 = crippled or 0 = not crippled) and age (A), County ($Cntr$), sex (S) and body mass (W) of barnacle geese in Denmark, Germany and the Netherlands, with number of parameters (k), corrected Akaike information criterion ($AICc$), $\Delta AICc$ and Akaike weight. Table includes the top model (lowest $AICc$), the candidate models with an $\Delta AICc < 2$ and the null (constant) model

Model	k	AICc	$\Delta AICc$	w
$C \sim A + Cntr$	5	1296.8	0.00	0.43
$C \sim A + Cntr + S$	6	1298.1	1.26	0.23
$C \sim A + Cntr + W$	6	1298.1	1.27	0.23
$C \sim constant$	2	1323.9	26.81	0.00

Table 7 Effects of age (A) and County ($Cntr$) assumed to influence crippling of barnacle geese in Denmark, Germany. As the second and third models with a $\Delta AICc < 2$ are more complex models (Table 6) the added variables S and W were assumed to be uninformative (Arnold 2010), therefore the results of only the $\Delta AICc = 0$ model are shown in this table. Age reference group: adult. Country reference group: The Netherlands

Variable	Estimate (β) ^a	SE	Z value	2.5%–97.5%	Effect ^b
Constant	-1.51	0.07	-19.7	-1.66 to -1.36	***
$A_{juvenile}$	-1.37	0.41	-3.35	-2.27 to -0.64	***
$Cntr_{Denmark}$	0.52	0.40	1.29	-0.32 to 1.27	
$Cntr_{Germany}$	-0.77	0.24	-3.20	-1.27 to -0.32	**

The model-averaged parameters of the two top models ($\Delta AICc \leq 2$) provided support for differences in the number of embedded pellets in different species (Table 11), with more pellets in greylag and Canada goose (*Branta canadensis*), and less in greater white-fronted goose and Eurasian

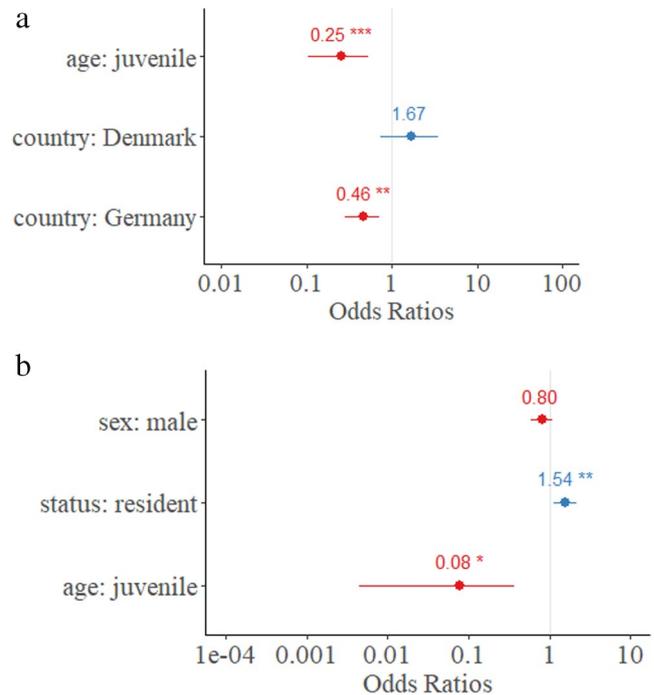


Fig. 2 (a) Odds ratios resulting from the top model of generalized linear models with a binomial distribution and a logit link function, testing the effect of age and country on crippling (1 = crippled or 0 = not crippled) of barnacle geese in three countries: The Netherlands, Denmark and Germany. Age reference group: adult. Country reference group: The Netherlands. (b) Odds ratios resulting from model averaging of generalized linear models with a binomial distribution and a logit link function, testing the effect of age, sex, and status (resident or largely migrant) on crippling (1 = crippled or 0 = not crippled) of barnacle geese in The Netherlands. Age reference group: adult. Status reference group: migrant

Table 8 Effects of age (*A*) and county (*Cntr*) assumed to influence crippling of barnacle geese in Denmark, Germany. As the second and third models with a $\Delta AICc < 2$ are more complex models (Table 6) the added variables *S* and *W* were assumed to be uninformative (Arnold 2010), therefore the results of only the $\Delta AICc = 0$ model are shown in this table. Age reference group: adult. Country reference group: The Netherlands

Variable	Estimate $(\beta)^\alpha$	SE	Z value	2.5%–97.5%	Effect ^b
Constant	-1.51	0.07	-19.7	-1.66 to -1.36	***
<i>A</i> _{juvenile}	-1.37	0.41	-3.35	-2.27 to -0.64	***
<i>Cntr</i> _{Denmark}	0.52	0.40	1.29	-0.32 to 1.27	
<i>Cntr</i> _{Germany}	-0.77	0.24	-3.20	-1.27 to -0.32	**

Table 9 Effects of age (*A*) and county (*Cntr*) assumed to influence crippling of barnacle geese in Denmark, Germany. As the second and third models with a $\Delta AICc < 2$ are more complex models (Table 5a) the added variables *S* and *W* were assumed to be uninformative (Arnold 2010), therefore the results of only the $\Delta AICc = 0$ model are shown in this table. Age reference group: adult. Country reference group: The Netherlands

Variable	Estimate $(\beta)^\alpha$	SE	Z value	2.5%–97.5%	Effect ^b
Constant	-1.51	0.07	-19.7	-1.66 to -1.36	***
<i>A</i> _{juvenile}	-1.37	0.41	-3.35	-2.27 to -0.64	***
<i>Cntr</i> _{Denmark}	0.52	0.40	1.29	-0.32 to 1.27	
<i>Cntr</i> _{Germany}	-0.77	0.24	-3.20	-1.27 to -0.32	**

Table 10 Generalized linear models with a Poisson distribution and a logit link function examining the relationship between pellet number and (*A*), sex (*S*), species (*Sp*) and body mass (nested in species) of 9 waterfowl species in Europe, with number of parameters (*k*), corrected Akaike information criterion (AICc), $\Delta AICc$ and Akaike weight. Table includes the top model (lowest AICc), the candidate models with an $\Delta AICc < 2$ and the null (constant) model

Model	k	AICc	$\Delta AICc$	w
$P \sim A + S + Sp$	12	1823.6	0.00	0.50
$P \sim A + Sp$	12	1824.8	1.18	0.28
$P \sim constant$	2	1874.5	50.95	0.00

wigeon, compared to barnacle goose (Fig. 4). Brent goose showed a tendency for having fewer pellets than barnacle goose (Fig. 4). The results further showed that adults carried more embedded pellets than juveniles (Fig. 4), and a tendency for males having more embedded pellets than females.

Discussion

We found that crippling rates for nine waterfowl species in Northwest Europe varied between 4% and 33% among species and averaged 17% across all species, or 19% if only

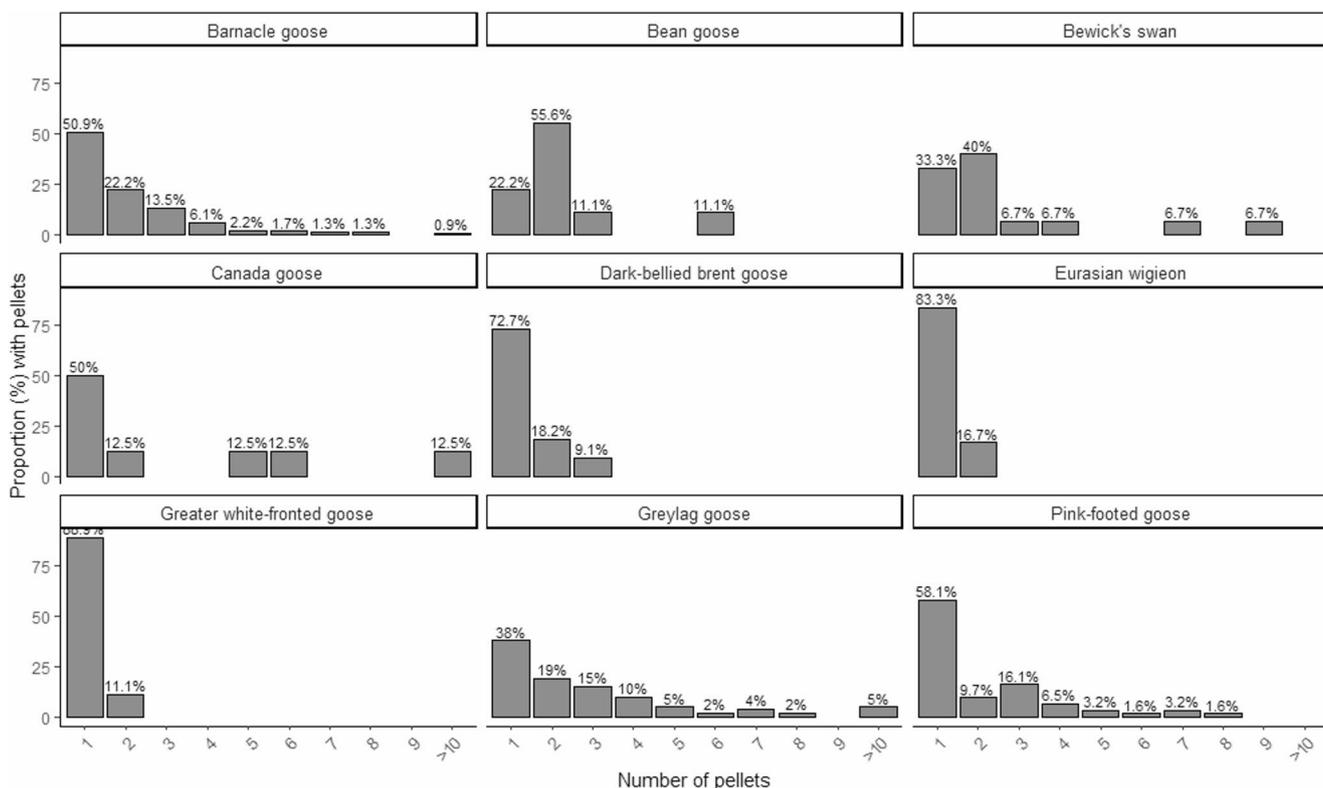


Fig. 3 The proportion of x-rayed individuals with different numbers of embedded shotguns of the total number of birds with at least one pellet, for adults of nine waterbird species in Denmark, Germany, The Netherlands, Lithuania, Norway, and Sweden, in 2017–2022

Table 11 Effects of age (*A*), species (*Sp*) and sex (*S*) assumed to influence pellet numbers in 9 waterfowl species in Europe, with model-averaged parameter estimates and 95% confidence intervals for each variable in the two most strongly supported models (Table 6a). Age reference group: adult. Species reference group: barnacle goose. Sex reference group: female

Variable	Estimate (β) ^α	Conditional \widehat{SE}_{β}	Z value	2.5%–97.5%	Effect ^b
<i>Constant</i>	0.70	0.058	12.0	0.59 to 0.82	***
<i>A_{juvenile}</i>	−0.39	0.19	2.02	−0.78 to −0.01	*
<i>S_{male}</i>	0.11	0.06	1.80	−0.01 to 0.23	.
<i>Sp_{Bean goose}</i>	0.10	0.22	0.43	−0.34 to 0.54	.
<i>Sp_{Bewick's swan}</i>	0.24	0.16	1.45	−0.08 to 0.56	.
<i>Sp_{Dark-bellied brent goose}</i>	−0.44	0.23	1.94	−0.89 to 0.00	.
<i>Sp_{Canada goose}</i>	0.61	0.19	3.26	0.24 to 0.97	**
<i>Sp_{Greater white-fronted goose}</i>	−0.63	0.32	1.97	−1.26 to −0.00	*
<i>Sp_{Greylag goose}</i>	0.38	0.07	5.24	0.24 to 0.53	***
<i>Sp_{Pink-footed goose}</i>	0.03	0.10	0.32	−0.16 to 0.22	.
<i>Sp_{Eurasian wigeon}</i>	−0.54	0.25	2.20	−1.03 to −0.05	*

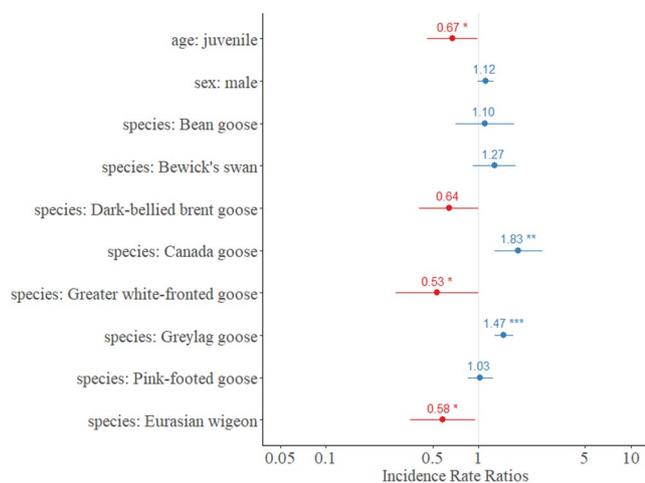


Fig. 4 Incidence Rate Ratios resulting from model averaging of generalized linear models with a Poisson distribution, testing the effect of age, sex, and species on the number of embedded pellets for crippled individuals of 9 waterfowl species in Europe. Age reference group: adult. Species reference group: barnacle goose. Sex reference group: female

adult birds were considered. This is within the range of previously reported crippling rates of geese and swans, which varied between 12 and 62% in a range of localities and species (e.g., Grieb 1970; Norman 1976; Anderson and Sanderson 1979; Humburg et al. 1982; Noer and Madsen 1996; Holm and Madsen 2013; Newth et al. 2019; Månsson et al. 2024). We found relatively high crippling rates in some species, such as greylag goose (28%) and in the bewick’s swan population (33%). The high crippling rates found in the bewick’s swan in the present study are in line with earlier studies of the species (23–39%) and show evidence of a continued exposure to poaching despite it is fully protected status across the entire range (Rees et al. 1997; Newth et al. 2019, 2022). This is alarming, as the species is demographically vulnerable to hunting (Nagy et al. 2012; but see Nuijten et al. 2020).

Apart from Eurasian wigeon, we found consistently higher crippling rates in adults than juveniles, but no difference between the sexes. For example, 16% of adult and 5% of juvenile barnacle geese in our sample carried pellets in their tissue, which is similar to the 13% crippling rate in adult and 6% in juvenile barnacle geese that were examined in Denmark in 2009–2011 (Holm and Madsen 2013). In general, juveniles often comprise a relatively high proportion of bagged waterbirds (Grieb 1970; Wright and Boyd 1983; Francis et al. 1992) a pattern that has been proven to be related to flocking behaviour of goose families (Madsen 2010). Geese and swans are long-lived species, and hence can experience consecutive hunting seasons or derogation events during their lifetime. The detected high crippling rates in adults may thus most probably be the result of cumulative exposure. The tendency of a higher number of pellets found in adults compared to juveniles in our examination also points in this direction. The fact that Eurasian wigeon is shorter-lived than the other, larger species (Speakman 2005) may explain why we found no difference between adult and juveniles. Alternatively, Eurasian wigeon may succumb more often to crippling compared to the larger species, leading to lower degrees of accumulation of pellets over life.

Waterfowl can potentially be subjected to hunting along their whole flyway, but assessments of their crippling rates outside core wintering areas have been rare (e.g. Guillemain et al. 2007; Newth et al. 2011; Månsson et al. 2024). We found that crippling rates varied between countries, shedding light on the likely origin of crippling. The relatively high crippling rates of wintering barnacle geese in The Netherlands compared to those in Germany may be explained by the relatively more frequent - in space and time - derogation shooting in The Netherlands compared to Germany, where derogation shooting occurs only in a single federal state (Schleswig-Holstein) and with much smaller numbers shot (Jensen et al. 2022). Furthermore, the winter sample

from The Netherlands included an unknown yet probably larger proportion of resident breeding birds than the German sample, and our data indicate more crippling of sedentary barnacle geese (21% of adults in The Netherlands were crippled) than the (mostly) migratory barnacle geese sampled outside the breeding period (15% of adults were crippled).

On average, the larger species in our sample exhibited the highest mean crippling rates, with brent goose and Eurasian wigeon having lower, and greylag goose and bewick's swan higher crippling rates compared to the intermediately-sized barnacle goose. As we did not find that individual body mass within species was an important determinant of crippling rate, crippling rates vary more with the more considerable size differences between species than the size differences within a species. Exceptions to this, such as the relatively low crippling rate for heavy Canada geese in our sample, may be mostly due to the locally low exposure to shooting in our sample of individuals for this species. To some extent, the higher crippling of the heavier species reflected our results of embedded pellets, with larger greylag and Canada goose carrying more embedded pellets on average than barnacle goose, and fewer in Eurasian wigeon; the exception being lower numbers of pellets detected in greater white-fronted goose than barnacle goose. In addition to being exposed to accumulation of pellets during their longer lives, larger species with thicker muscle and fat layers that might protect vital organs, and consequently decrease likelihood of fatal injuries from pellets. Other plausible reasons for the higher crippling of larger species are that larger birds have a larger area of exposure to being hit, or they may generally be shot at more frequently than smaller waterfowl species. Lastly, larger species may face a higher risk of being shot at longer ranges than smaller species, as larger birds may appear to be closer than they actually are.

Given the high crippling rates of some of the studied species in the present study, a management strategy needs to be developed together with hunters and other key stakeholders to minimize crippling to increase animal welfare and waterbird conservation status and prevent lead poisoning of scavenging raptors (e.g., Helander et al. 2009, 2021). Because crippling rates, to a large extent, are affected by hunters' choice of ammunition and shotguns and assessment of shooting ranges at which birds are realistically downed (Noer et al. 2007), guidelines should focus on improving hunters' practices and behaviour to reduce crippling. For migratory birds, such measures are required along the flyway, particularly in countries with high bag sizes and frequent derogation shooting. That such measures can be effective in reducing crippling has been shown; for example, Denmark's National Action Plan to reduce crippling of wildlife reduced the crippling rate in adult pink-footed geese (*Anser brachyrhynchus*) from approximately 36% to 18% between

1997 and 2005 (Noer et al. 2007), primarily due to reduced shooting distances. Similarly, the incidence of embedded shotgun pellets (i.e. crippling rate) in adult common eider (*Somateria mollissima*) females declined from 34% to 5.5% between 1997 and 2011 (Holm and Haugaard 2013) with studies conducted in 2021–2022 suggesting continuous improvement (Liljebäck et al. 2023). Common eider males, which were exposed to hunting outside the area of the action plan, showed a lower rate of decline. On the other hand, crippling rates for geese in Illinois declined from 21% to 9% in the absence of any formal program, suggesting that the decline in crippling rates in this case may rather have been related to different shot material used after a ban on lead ammunition, improvements in ammunition technology, or more widespread (undocumented) changes in hunting practices (Ellis and Miller 2022). In such and other cases, x-raying to determine crippling rates is needed to evaluate the effectiveness of measures to reduce crippling, or to monitor levels of (illegal) hunting (for e.g., bewick's swan; Newth et al. 2011, 2022).

Future research

The high crippling rates found in sedentary barnacle and greylag geese in The Netherlands suggest that for these species derogation shooting is of special concern. The reasons for this remain unknown and ought to be addressed by targeted field investigations. Importantly, an assessment of the total number of individuals targeted by shot is essential for a proper interpretation of the frequencies measured by x-raying, as crippling rates vary not just with hunters' behaviour, their experience and materials used, but also with the proportion of birds being shot of the total population. Clausen et al. (2017) therefore introduced the term "crippling ratio", i.e. the percentage of individuals crippled divided by the population harvest rate. This allows for an evaluation of hunters' performance in a way that accounts for differences in harvest rate, by estimating the number of geese crippled for each goose bagged. They found that the crippling ratio of juvenile pink-footed geese dropped from 1.00 in 1992 to 0.11 in 2016, which corresponds to an 89% reduction in crippling frequency. Among adult birds the ratio dropped from 9.75 to 1.99 during the same period, i.e. by 80%. Clausen et al. (2017) ascribed this reduction to effective awareness campaigns, training of hunters and adjustment of hunting techniques in Denmark and Norway, where this species is hunted. The assessment of crippling ratio depends not only on crippling rates, but also on knowledge of the population size prior to the hunting season and total hunting bag divided into juveniles and older birds (Clausen et al. 2017). Presently, there is limited information on the total and age divided bags for many of the species examined here,

which limits the use of crippling ratios to determine hunting performance, or improvements thereof, although crippling rates themselves might be used as a proxy of harvest rate to determine annual bags (Holm and Madsen 2013). As a first requirement for an evaluation of hunter's performance, improved knowledge of the hunting bag along the entire flyway of waterfowl species is needed.

At present, our data provide limited information on long-term effects of crippling on the species involved. Madsen and Noer (1996) found that pink-footed geese with embedded pellets had a significantly lower survival (0.77) than non-carriers (0.87), and that this difference was constant between years and cohorts. Tavecchia et al. (2001) demonstrated that survival of crippled mallards (*Anas platyrhynchos*) was 19% lower than birds without embedded pellets. Differences in survival rates may be explained by shotgun pellets, of any metal, having a longer-term impact on essential body functions or biochemical toxic impacts (via embedded lead shot). However, Madsen and Rigét (2007) found no indications for differences in body condition between individuals with and without embedded pellets. But common eiders, carrying embedded pellets, were reported to experience difficulties maintaining adequate body-fat stores in midwinter, which may lower their reproductive success and survival (Merkel et al. 2006). In general, studies on negative effects of crippling on survival and body condition requires frequent sampling of the population or follow up of individual bird life history traits.

The crippling of waterbirds along flyways may have consequences for the wider system into which pellets are introduced, especially if the crippling occurs with lead shot. Our data do not include separation of pellets according to material, but likely include both non-lead and lead ammunition. There is a total ban on lead ammunition in few EU countries, including The Netherlands and Denmark, and to prevent lead poisoning of wildlife the use of lead pellets over EU wetlands has recently been banned under the REACH regulation (registration, evaluation, authorization and restriction of chemicals), which has been implemented in 2023. Nevertheless, lead ammunition is still commonly used along the flyway of the migratory waterbirds examined here, including barnacle, pink-footed, bean and greater white-fronted geese, as well as Eurasian wigeon and bewick's swan (Thomas et al. 2019). As such, migratory waterbirds may transport lead into North-West European systems where lead ammunition is prohibited, with potential toxic impacts on for example scavenging eagles (Pain et al. 2019; Monclús et al. 2020; Helander et al. 2021). The potential transport of lead pellets along migration corridors of waterbirds is still, to our knowledge, not investigated in depth. Further information on the occurrence of lead and non-lead pellets in crippled waterbirds is needed to assess risks of lead poisoning to other

wildlife, also in areas where lead shots are rarely used. This could be done by dissecting birds where pellets are detected by x-ray, or using sensitive metal detectors that can discriminate between lead and non-lead pellets.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Clinical trial number not applicable.

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