Received: 6 June 2022 | Accepted: 29 August 2022

DOI: 10.1111/1365-2664.14297

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Effects of multiple targeted repelling measures on the behaviour of individually tracked birds in an area of increasing human–wildlife conflict

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Funding information
Finnish Ministry of Environment

Handling Editor: Marc-André Villard

Abstract

1. Some animal populations are rapidly increasing in numbers and expanding their ranges, leading to intensified human–wildlife conflicts. A wide range of tools has been developed to repel animals from areas where they are suspected to cause damage. For waterfowl, direct comparisons of multiple repelling methods have so far focused only on species´ presence, total numbers, cost effectiveness or subsequent damage assessments, but not on individual behaviour.
2. Here, we investigated the individual responses of free-flying geese to three repelling methods using high-resolution tracking data. In an experimental setup, tracked individuals were repelled by human approach, gunshot sound or handheld lasers.
3. We found that repelling success and return time to the field where the repelling took place increased when individuals were repelled multiple times. Travel distances after the repelling events were longer after human approach and gunshot sound compared to the handheld laser treatments. In spring, the probability to return to the same field was higher after repelling with handheld lasers, but no difference between treatments was evident in autumn. We observed no increase in the probability to visit accommodation fields, where geese were allowed to forage and were not repelled, after the repelling events.
4. *Synthesis and applications*. We found no strong differences between the three methods regarding the repelling effectiveness and the resulting behaviour of the tracked geese. However, the higher return rates of individuals after repelling with handheld lasers in spring suggest that this method might be less effective in situations with bright sunlight or very large aggregations of geese. Apart from these limitations, we can recommend handheld lasers for repelling as they might reduce energetic losses for the geese and disturbance of non-target wildlife. Since repelling by gunshot sound and handheld lasers was twice as fast as repelling by human approach, those methods will reduce working hours by 50% and therefore be more cost-effective in practice.

KEYWORDS
accommodation field, agricultural conflict, barnacle goose, branta leucopsis, disturbance, laser, management, shooting, tracking

1 | INTRODUCTION

Animals can pose a threat to the livelihoods of humans, and measures are taken to remove wildlife from areas where it is suspected to cause damage, for example, in agricultural areas or airports (Allan, 2000; Bradbeer et al., 2017; Koehler et al., 1990; Rivadeneira et al., 2018). To repel animals, a wide range of chemical, visual and auditory methods has been tested (Aguilera et al., 1991; Cummings et al., 1991; Dieter et al., 2014; Gilsdorf et al., 2002; Mason et al., 1993; Rivadeneira et al., 2018; Werner & Clark, 2006). In practice, repelling methods need to be simple and cost-effective, especially when large areas need to be protected.

In repelling of birds, widely used methods are (1) the direct approach by a human and/or a vehicle until the birds take off, or (2) the scaring of birds acoustically with gun shots, fireworks or gas cannons (Gilsdorf et al., 2002; Simonsen et al., 2016, 2017; Vickery & Summers, 1992). Lethal scaring, that is, shooting a number of birds from a flock, is also used to reduce crop damage (Hitchcock et al., 2019; Månsson, 2017). A rather new and non-lethal method is repelling with lasers, where the intense light causes aversive behaviour in birds (Blackwell & Bernhardt, 2000). This method can also be applied in sensitive areas, such as nature reserves or tourist areas, where shooting is not an option. Furthermore, the specificity of handheld lasers is suggested being higher so that non-target species sharing the same areas will not be disturbed (Clausen et al., 2019).

Disturbance, for example, through repelling or shooting, significantly alters the behaviour of wild animals. When heavy birds have to take to the air more frequently, their nutritional demands are elevated, resulting in increased consumption compensating for the loss of energy (Nolet et al., 2016). Disturbance at low frequencies can cause birds to stay even longer in particular areas, as they need more time to refuel sufficiently (Bauer et al., 2018; Béchet et al., 2004), or because they are pushed to less favourable habitats (Tombre et al., 2005). Uncoordinated disturbance might only redistribute the birds locally (Klaassen et al., 2006). Therefore, systematic disturbance at high frequencies is needed to limit crop damage (Simonsen et al., 2016).

Frequent disturbance can have more wide-ranging consequences for birds and can lead to changes in their migration schedule. Disturbed birds may return to previous stop-over sites and/or leave areas earlier (Béchet et al., 2003), which will cause longer stays and elevated damage at other sites (Bauer et al., 2018). During spring migration, disturbance can lead to reduced fat deposition and poorer body condition in geese (Klaassen et al., 2006; LeTourneux et al., 2021). This may result in lower breeding success (Béchet et al., 2004), since geese are capital breeders. Therefore, local management decisions have the potential to affect population stability, and should consider effects all along the species' flyway (Bauer et al., 2018).

Direct comparisons of multiple repelling methods have so far focused on the presence of birds, total bird numbers, cost effectiveness or subsequent grazing intensity (Heinrich & Craven, 1990; McKay & Parrott, 2002; Vickery & Summers, 1992). Only few studies have investigated the behavioural response of individual birds towards targeted repelling with different methods (e.g. in gulls, Thiériot et al., 2015). The migratory behaviour, habitat use and fattening of radio-tracked individuals before and after the establishment of spring hunting have been studied in greater snow geese *Anser caerulescens* (Béchet et al., 2003, 2004), and the flight durations after disturbance were measured in greater white-fronted geese *A. albifrons* (Nolet et al., 2016). However, studies directly comparing the effectiveness of multiple repelling techniques and their effects on individual geese are lacking, in spite of the importance of such knowledge for land-owners, management and policy decision-makers. Data on the individual level allow the estimation of the true effectiveness of repelling (Pekarsky et al., 2021), and to interpret changes in distribution (Tombre et al., 2019). For example, when birds are returning to a sensitive area after repelling, it is important to know whether these are inexperienced individuals, or whether there are returning individuals that might habituate towards the repelling method (York et al., 2000).

Rapid development of satellite tracking technology now enables us to investigate the behaviour of free-flying birds with unprecedented resolution in both space (meters) and time (minutes). In this study, we used high-resolution tracking data of barnacle geese *Branta leucopsis* to investigate the response of free-flying individuals to alternative targeted repelling measures. Changes in climate and agricultural practices have led to enhanced conditions for Arctic breeding geese (Doyle, Cabot, et al., 2020; Doyle, Gray, & McMahon, 2020; Fox & Abraham, 2017; Mason et al., 2018). Increasing goose populations are fuelling human–wildlife conflicts in East Asia, Europe and North America (Amano et al., 2007; Fox & Leafloor, 2018; Fox & Madsen, 2017). The superabundance of geese has raised concerns regarding negative effects on tundra vegetation, air traffic and disease transmission (Buij et al., 2017). High economic losses come from reduced agricultural yields caused by geese grazing, especially in grasslands or winter cereals (Bjerke et al., 2021; McKay et al., 1996; Percival & Houston, 1992). One strategy to alleviate this conflict is the establishment of accommodation areas (hereafter 'goose fields'), where geese are allowed to feed undisturbed (Vickery & Gill, 1999). To concentrate geese on such fields, and to protect valuable crops, geese are repelled from the most vulnerable fields outside the accommodation area. However, there is

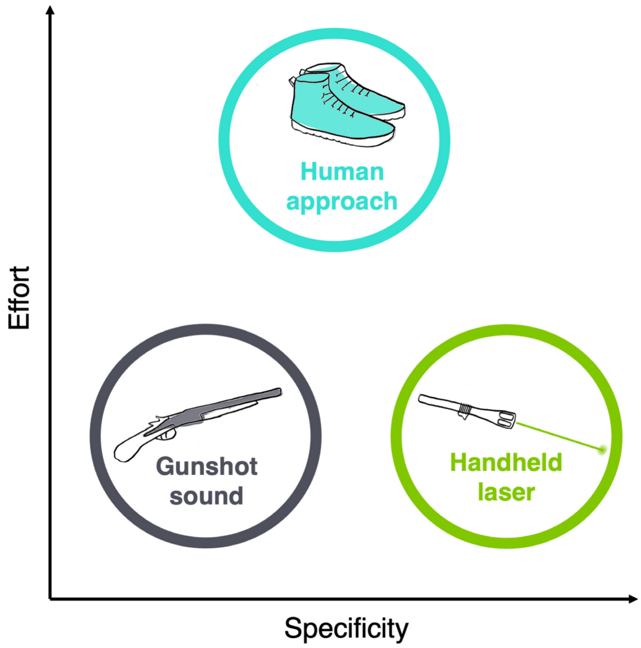

FIGURE 1 Repelling methods used in this study. *Specificity* is defined as the level of disturbance of non-target wildlife, while *Effort* is defined as the expected time needed for a person to repel birds from an area. Repelling by gunshot sound is expected to cause highest disturbance of non-target wildlife, whereas repelling by handheld laser is considered the most specific method. Repelling by human approach is expected to take more effort compared to gunshot sound and handheld laser treatment.

no evidence so far that geese learn to favour such goose fields or to avoid repelling areas (Koffijberg et al., 2017).

The barnacle goose has seen the strongest increases in numbers and is now the most common goose in Europe (Fox & Leafloor, 2018). Very recently, barnacle goose populations have shifted their main stopover sites northward (BirdLife Finland, 2021; Tombre et al., 2019), possibly as a response to the mismatch between spring arrival and the peak of food availability (Lameris et al., 2018; Tombre et al., 2019). In eastern Finland, numbers of geese staging belonging to the breeding population of the Russian Arctic have increased from a few individuals to almost a million since 2006, creating production challenges for local farmers in spring and autumn (BirdLife Finland, 2021). Given that the barnacle goose population of the Russian Arctic continues to grow substantially (Rozenfeld et al., 2021), management strategies need to be developed (Jensen et al., 2018).

In an experimental setup, we repelled individually tracked barnacle geese with three different methods, which differ in specificity and effort (Figure 1). Here we present data on behavioural responses after the repelling treatment and compare the effectiveness of the repelling methods. Furthermore, we investigated whether the repelling caused individual geese to visit goose fields (i.e. fields where the geese are allowed to graze).

We considered that the most effective repelling method from a management perspective should result in (1) the highest probability that individuals are repelled from the target field, (2) the lowest probability that individuals would return to the very same field and (3) the lowest travel distances resulting in lower energy expenditure limiting compensatory grazing.

2 | MATERIALS AND METHODS

2.1 | Study area

We conducted the fieldwork in Northern Karelia, Finland, an important stop-over area for barnacle geese during spring and autumn migration (Figure 2a). Our study area included 520 km^2 of fields (mean field size 2.1 ha, range 0.01–74.4 ha), of which ~1% were declared as goose fields (Figure 2b). Fodder plants for livestock were grown on all fields (including goose fields) in the area, such as grasses (e.g. *Phleum*, *Lolium*) and clover.

2.2 | Catching and transmitters

We caught birds with a cannon net on fields during 11–12 May and 19 September 2021. We equipped 70 adult barnacle geese (30 males and 20 females in spring, 10 males and 10 females in autumn) with solar-powered GPS-GSM/GPRS transmitter neckbands (OrniTrack OT-NL40-3GC, Ornitela, UAB, Lithuania) and an individually numbered metal leg ring. Permissions to catch and mark as well as to tag geese with satellite transmitters were issued by the Centre for Economic Development, Transport and the Environment (ELY-keskus, permission numbers VARELY/1288/2021 and VARELY/1313/2021). We followed all ethical guidelines by the Finnish Bird Ringing Centre. The tags weighed 22 g, which added <2% of weight to the lightest bird. We set the GPS resolution to 10 min, and the data transmission interval to 1 h. If the battery level would drop below 50%, we programmed the transmitters to record positions and to transmit data less frequently. All tracked birds belonged to the population breeding in the Russian Arctic which spent the non-breeding season in southern Sweden, Denmark and along the North Sea coast in Germany and the Netherlands (Figure 2).

2.3 | Repelling experiments

We started with the experiments >24 h after the birds received their transmitters and only with those birds which had stayed in the study area and which resumed normal behaviour, visible as regular movements between feeding and roosting sites (from now on: experimental birds). Experiments were conducted 14–22 May and 21–24 September 2021. Weather was mostly sunny in spring and overcast in autumn. We localized flocks of geese containing experimental birds based on the most recent transmitted positions. To ensure the presence of the experimental birds in the flock, we waited for the transmitters to send up-to-date locations before starting

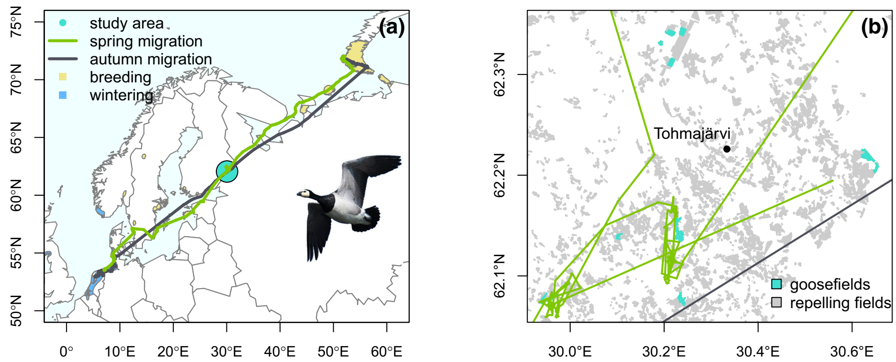

FIGURE 2 (a) Position of the study area in Finland and migration route of one representative barnacle goose ('RAJ') between its breeding site on Novaya Zemlya, Russian Federation, and its wintering area in Friesland, The Netherlands. Note that not all tracked individuals have visited the study area during both spring and autumn migration. Species distribution range based on BirdLife International (2022). (b) Distribution of fields in the study area around Tohmajärvi, Northern Karelia, and movement of one individual barnacle goose ('RAJ') within the study area. Colours of the track correspond to Figure 2a.

the repelling. We experimentally repelled these flocks from fields with three different methods: (1) Repelling by walking towards the flock until the birds´ take-off; (2) Repelling by pointing a handheld laser (Handheld 500 by Bird Control Group, Delft, The Netherlands; power < 500 mW, 520 nm wavelength of green continuous wave) at birds; and (3) Repelling by shooting one or two blank shots with 9 mm signal revolvers (Models: Reck. Mod. Python cal 380 RK and RÖHM cal. 9 mm RK). The sound pressure levels at 30 meters from the gun were L_{peak} = 123 dB (maximum signal level) and L_E = 87 dB (total energy of a gunshot normalized to 1 second). In an open field doubling the distance from the gun reduces the level by six decibels.

The persons conducting the treatments wore a brightly coloured safety vest and approached geese in all treatments close enough (usually 90–150 m) that the geese clearly observed (heads up, slightly cautious behaviour visible) the approaching human. We aimed to repel all individuals with each of the three methods. The minimum time between two experiments was set to 1 h, and not more than three experiments were conducted with the same individual on the same day. For each experiment, we recorded date, time needed for repelling, the name of the person conducting the experiment, the ID of the experimental bird and the repelling treatment. Furthermore, we estimated the size of the flock in the set of fields with the experimental bird. Repelling experiments were only conducted with individuals on fields that were not declared as goose fields.

2.4 | Repelling effects

We defined the experimental time as the start of the experiment, that is, when the first shot was fired, or the laser was pointed at the geese, or when we entered the field and started walking towards the flock. We defined the experimental position as the last transmitted GPS position of an experimental bird before the experimental time (mean time lag between last transmitted position and experimental time 8 min, range 1–54 min, n = 191). While we did not see the target bird in all cases, we are confident that the bird was still there when there was a flock, as typically the whole flock takes off when there is disturbance. The experimental field was defined as the field where the experimental position came from.

To analyse the effects of the repelling measures, we calculated the following response variables. First, we defined *repelling success*. If the first position of an experimental bird in the hour after the experiment came from outside the experimental field, we counted this trial as success (1). If the first position in the hour after the experiment came from inside the experimental field, we counted this trial as not successful (0). Second, we calculated the *travel distance* (in meters) as the sum of distances between the experimental position and all positions (n = 1–6) within 1 h after the experimental time in chronological order. We calculated these distances using the st_distance function in R package SF (Pebesma, 2018). Repelling success and travel distance were not calculated for experiments when we did not receive any positions of an experimental bird in the hour after the experimental time.

Third, we analysed whether individuals had returned to the experimental field (*return probability*). We defined birds as returned (1) if we received at least one more position after the experimental time from the experimental field, whereas we defined birds as not returned (0) if we received no position after the experimental time from the experimental field. Fourth, we calculated the *return time* (in hours) as the time between the experimental time and the time of the first return position of an experimental bird from the experimental field.

Furthermore, we analysed whether the probability that an individual is visiting a goose field is affected by the repelling measures (*probability of goose field use*). If at least one position in the 24 h after an experiment fell on a goose field, we counted this trial as success (1).

We considered different tracked individuals within the same field as independent, given that foraging flocks are labile and individuals often respond differently towards a repelling event (Béchet et al., 2004), which was the case also in our study (different individuals e.g. moved to completely different locations after repelling). All spatial analyses were carried out in R Version 4.0.1 (R Core Team, 2021) using the packages RASTER (Hijmans & van Etten, 2012), RGDAL (Bivand et al., 2015) and SP (Pebesma & Bivand, 2005).

2.5 | Statistical analysis

We performed generalized linear mixed-effects models in a deterministic Bayesian framework to predict the response of experimental birds towards the three different repelling measures in spring and autumn. Models were built using Integrated Nested Laplace Approximation (INLA) with the R-INLA package (Rue et al., 2009). The INLA algorithm is an analytic approximation using the Laplace method, which is less computationally intensive and thus faster than the simulation-based Monte Carlo integration (MCMC; Rue et al., 2009). Furthermore, INLA is a great way to handle spatial autocorrelation (consideration of the similarity of nearby locations) in models (Zuur & Ieno, 2018). While there are possibilities to control for autocorrelation in simulation-based methods like a conditional autoregressive (CAR) structure in R package BRMS (Bürkner, 2017), INLA is computationally efficient, as it allows to use a Stochastic Partial Differential Equation (SPDE) to estimate the spatial autocorrelation of our data while using a Gaussian Markov Random Field to approximate the full Gaussian field using a Matérn covariance structure and Delaunay triangulation (Lindgren et al., 2011). The so-called 'mesh' with prediction locations is built out of discrete sampling locations by adding further vertices to reduce the number of required triangles (see Supporting Information S1). We used the function inla.mesh.2d() with max.edge = c(1.5, 3) and cutoff = 0.0001. We expected spatial autocorrelation in our data as geese might show differences in behaviour depending on where the experiment was carried out. For example, travel distance and return time might depend on the distance towards preferred feeding and roosting sites, and repelling success might be affected by potential additional repelling activities of farmers in certain areas.

We built five different models with repelling success, travel distance, returning probability, return time and probability of goose field use as dependent variables. Treatment (direct human approach, handheld laser, gunshot sounds), treatment number (counting the number of experiments each individual has experienced), season (spring, autumn) and their interactions (treatment × treatment number, treatment × season, treatment number × season) were included as independent variables (Table 1). As random effects, we included individual identity (factor) and start time (continuous) of the experiment. We used INLA default priors, which are flat priors for the regression coefficients. The R code used to set the SPDE PC-priors can be found in Supporting Information S1.

For the models predicting repelling success, return probability and probability of goose field use, we used a binomial error distribution with logit-link. For the models predicting travel distance and return time, we performed models using a gamma error distribution with log-link.

TABLE 1 Structures of the alternative generalized linear mixed-effect models used to predict one of the five dependent variables (repelling success, travel distance, returning probability, return time and goose field use). We fitted the method of repelling ('treatment'), the number of experiments an individual has already experienced ('number') and the season (spring or autumn) and their interactions (marked with ':') as explaining variables. As random effects, we included individual and start time of the experiment in all model combinations.

Model nr.	Explaining variables and interactions
1	Treatment + season + number + treatment:season + season:number + number:treatment
2	Treatment + season + number + treatment:season + season:number
3	Treatment + season + number + treatment:season+ number:treatment
4	Treatment + season + number + season:number + number:treatment
5	Treatment + season + number + treatment:season
6	Treatment + season + number + season:number
7	Treatment + season + number + number:treatment
8	Treatment + season + treatment:season
9	Season + number + season:number
10	Treatment + number + number:treatment
11	Treatment + season + number
12	Treatment + season
13	Treatment + number
14	Season + number
15	Treatment
16	Season
17	Number
18	1 (null model)

We then performed a model selection upon each of those five models using the deviance information criterion (DIC; McCarthy, 2007; Wilberg & Bence, 2008). We selected of all possible combinations the model with the lowest DIC as best model, suggesting that this model explains our data best.

We finally simulated 1000 samples from the posterior of the fitted best model using the function inla.posterior.sample(). We present predicted mean values and the 95% credible interval (CrI). The 95% CrI is the range where the true value can be expected with a probability of 95%. We furthermore calculated the probabilities of different assumptions, for example, the slope being > or <0 as well as intercepts and means between treatments and seasons being different. A probability (*p*) of 1 indicates that there is very strong evidence for the assumption. A probability of 0 indicates the opposite: very strong evidence against the assumption. A probability of 0.5 indicates no evidence, respectively no difference.

3 | RESULTS

We conducted 53 repelling experiments resulting in 125 trials with 40 individuals in spring, and 44 experiments resulting in 66 trials with 19 individuals in autumn (53 individuals in total). The mean duration of the repelling experiments was longer for human approach (5.5 min, range 0–12 min) than for handheld laser (2.2 min, range 0–12 min) and gunshot sound (2.0 min, range 0–8 min).

The best model to predict repelling success included the factor's treatment number and season, as well as their interaction (Table 2). Repelling success increased with treatment number in spring ($p_{slope>0} = 0.89$) and even stronger in autumn ($p_{slope>0} = 0.98$, Figure 3c,d). In spring, a repelling success of 71% was predicted after the first repelling event, increasing continuously with treatment number to 91% after the sixth event (Figure 3c). In autumn, 75% of the birds were predicted to be repelled after the first repelling event, and more than 96% already after the second event (Figure 3d).

Individual variation was huge regarding the distance travelled in the hour following the repelling event (Figure 3a), with travel distances between 14 m (i.e. no displacement at all) and 59.3 km (i.e. continuing migration). In spring, at least two birds left the study area and started migration directly after a repelling event, as seen from straight flight trajectories in north-eastward direction (included in analysis, but not shown in Figure 3a). No individual started migration after a repelling event in autumn. The best model to predict the travel distance of individuals after the repelling event included only the repelling treatment (Table 2). Travel distances after the gunshot sound and human approach treatments were larger in comparison with those repelled by the handheld laser (1881 m and 1754 m vs. 793 m, $p_{mean\ gun>laser} = 0.97$, $p_{mean\ human>laser} = 0.93$, Figure 3a), while there was no difference between gunshot sound and human approach ($p_{mean\ gun>human} = 0.62$).

The best model for the probability of an individual to return to the field of the repelling event included the factor's treatment, season and their interaction (Table 2). In spring, the probability to return was 79% after the handheld laser treatment, 34% after the gunshot sound treatment, and around 48% after the human approach treatment (Figure 3e). In autumn, the probability to return was 47%, 62% and 74% after human approach, handheld laser and gunshot sound treatments, respectively (Figure 3f). The differences between handheld laser and gunshot as well as human approach treatment were strong in spring ($p_{mean\ gun<laser} = 1$, $p_{mean\ human<laser} = 1$), but less pronounced in autumn ($p_{mean\ gun<laser} = 0.20$ as well as $p_{mean\ human<laser}$ 0.84, respectively). In autumn, we found slight differences between human approach and gunshot sound (47 vs. 74%, $p_{mean\ human<gun} = 0.95$).

For those individuals that returned to the experimental field, the return time ranged from 1 min to 5 days. The best model contained only one explaining variable (Table 2) and predicted increasing return times with increasing treatment number ($p_{slope>0} = 0.90$).

TABLE 2 Best generalized linear mixed-effects models to predict repelling success, travel distance, return probability, return time and goose field use as selected by deviance information criterion (DIC). Given are all models with ΔDIC < 4 (where ΔDIC is the difference to the best model). For the structure of the models, compare the model number (nr.) with Table 1. Effect sizes are given in Supporting Information S2.

Dependent variable	Model nr.	DIC	ΔDIC
Repelling success	9	160.43	0.00
	14	161.36	0.93
	6	162.39	1.96
	11	162.69	2.26
Travel distance	15	3406.23	0.00
	18	3406.53	0.31
Return probability	8	245.78	0.00
	5	247.01	1.23
	2	248.54	2.76
	13	248.93	3.15
Return time	17	492.78	0.00
	14	493.22	0.45
	18	493.61	0.84
	16	493.75	0.97
	9	494.19	1.41
	13	494.72	1.94
	11	494.94	2.16
	12	496.02	3.24
	15	496.26	3.48
	6	496.45	3.68
Goose field use	18	250.49	0.00
	16	250.50	0.01
	12	250.58	0.08
	17	251.08	0.58
	15	251.10	0.61
	14	251.15	0.66
	11	251.84	1.35
	13	252.25	1.75
	8	252.55	2.06
	9	252.78	2.29
	10	252.96	2.47
	6	253.07	2.58
	7	253.66	3.17
	5	254.03	3.54

A mean return time of 0.8 h was predicted after the first repelling event, which increased to 2.9 h after the sixth event (Figure 3b).

The null model was selected as the best model to predict goose field use (Table 2). In 50% (95/191) of the repelling events, goose fields were visited at least once in the 24 h after repelling. All estimates for the selected models can be found in Supporting Information S2.

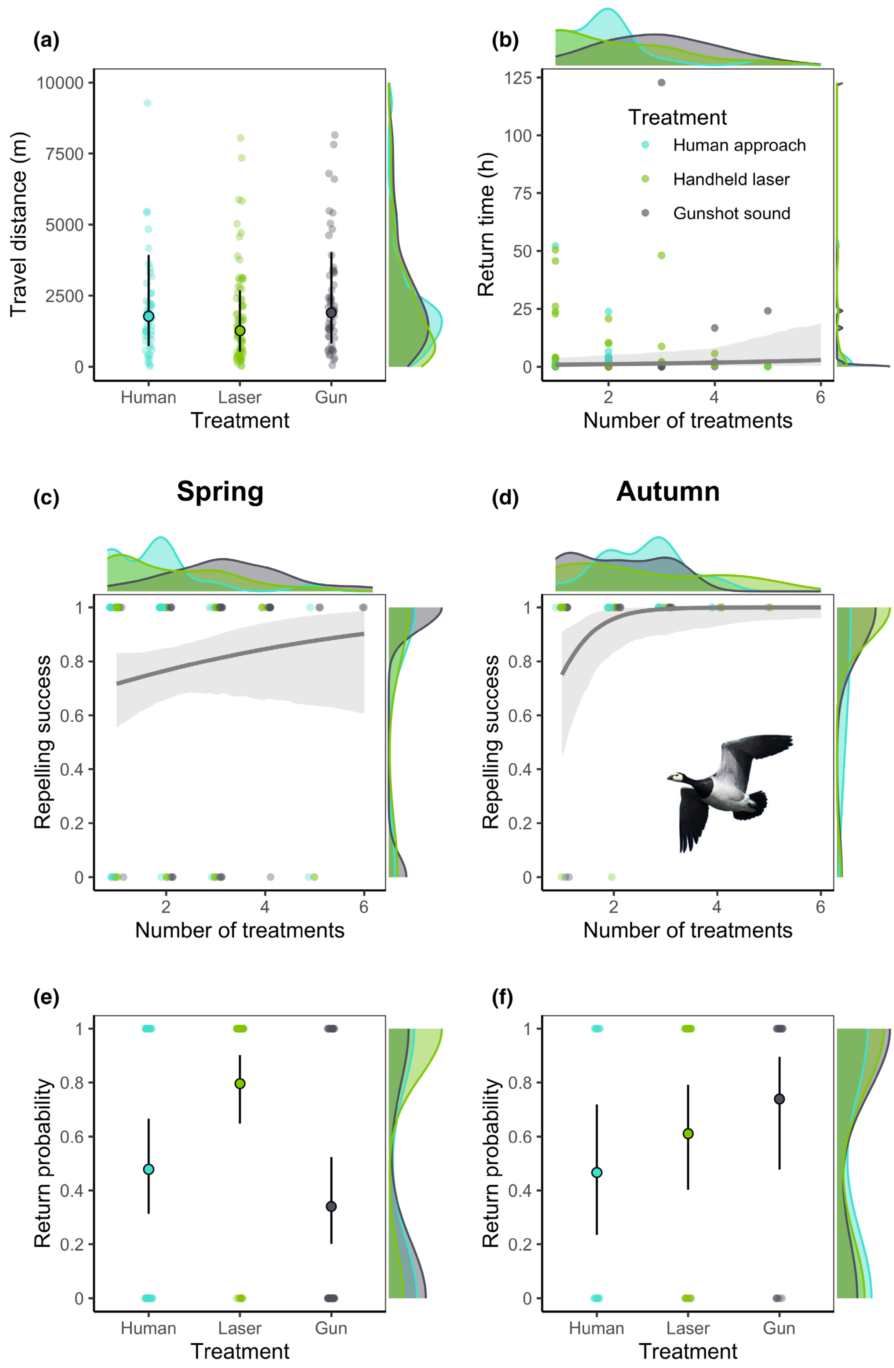

FIGURE 3 Individual responses of experimental birds towards three repelling methods: direct human approach (grey), handheld laser (green) and gunshot sounds (black). (a) Travel distances in the hour after the repelling event. Shown are the actual data (coloured dots) and the predicted means (big dots) plus 95% CrIs (black lines). (b) Time (in hours) until the return of an individual after the repelling event to the experimental field. Shown are the predicted probabilities (solid lines), the 95% CrIs (grey shade) and the actual data (coloured dots). (c, d) Probability of individuals being repelled from the target field depending on the number of treatment (i.e. how many times an experiment was already conducted with this individual) in spring (C) and autumn (D). Shown are the probabilities (solid lines), the 95% CrIs (grey shade) and the actual data (coloured dots). (e, f) Probability of an individual to return to the same field after the experiment in spring (E) and autumn (F). Shown are the actual data (coloured dots) and the predicted means (big dots) plus 95% CrIs (black lines). For all plots, the distribution of the numeric variable is shown on the right side for the variable on the y-axis, and on top of the plot for the variable on the *x*-axis. Non-overlapping CrIs imply a consistent difference. Note that outliers are not depicted in panel A (travel distance >11 km, $n = 11$ events).

4 | DISCUSSION

We found considerable plasticity in the response of barnacle geese towards targeted repelling measures. While some birds left the area and continued migration after being disturbed, others barely moved; and while some birds never returned to the field where they had been repelled from, others repeatedly returned to the same field just minutes after the disturbance (Figure 3). In the following, we discuss (1) differences in the responses of individual geese towards the three repelling methods, (2) the effects of repeated repelling on goose behaviour and (3) summarize the results to inform policy and management actions.

4.1 | Differences between repelling methods

As far as we know, our results provide first insights into individual behavioural responses towards three targeted repelling methods. The probability of an individual goose to return to the very same field where it was repelled was significantly higher when using a handheld laser in spring, whereas no strong differences in return probabilities were observed between repelling by human approach and gunshot sound (Figure 3). In autumn, geese responded equally towards repelling with handheld lasers compared to more offensive repelling methods (Figures 1 and 3). Travel distances of individual geese after experiments with handheld lasers were also significantly lower in spring compared to the other two methods, and again, no such difference was found in autumn (Figure 3). Very low travel distances could be an indication that an individual might have not taken flight at all, or took to the air only briefly and landed shortly after on the same field. On the other hand, lower travel distances also infer lower energy losses for an individual (Nolet et al., 2016). This could mean that birds will not have to increase feeding after being repelled by handheld lasers as much as after the repelling with the other methods to compensate for their energy loss, thereby limiting the total agricultural damage.

One possible explanation for the lower effectiveness of handheld lasers to repel birds in spring are the ambient light conditions. While the weather was mostly sunny in spring, most days were overcast and rather dark in autumn. In low-light conditions, the beam of the handheld laser is readily visible for birds, and can be perceived as a nuisance (Blackwell et al., 2002). In bright light, however, the laser beam is less visible, and might not disturb the geese sufficiently. Therefore, lasers have so far been mainly used to repel birds during dusk or dawn or from roosts during the night (Blackwell et al., 2002; Glahn et al., 2000; Gorenzel et al., 2002).

Another possible explanation for why handheld lasers were less effective in our study during spring might be related to flock size: in large concentrations of geese, only a few individuals will be directly exposed to the laser beam (Clausen et al., 2019), which means not all birds will perceive the threat. This might cause those individuals that did not perceive the threat to return quickly to the same field. The mean flock size during our experiments in spring numbered *c.* 15,000 individuals, but only *c.* 300 individuals in autumn, which might explain the overall better repelling success in the latter season. High repelling success but quick return were also documented when repelling crows at roosting sites with lasers (Gorenzel et al., 2002). As lasers have no biological meaning to birds, they might not be perceived as a substantial threat, and might therefore cause only short-term responses (Gorenzel et al., 2002). However, previous studies on geese revealed that birds would return to areas with constant laser repelling only 2–6 days after the end of the laser treatment (Elbers & Gonzales, 2021; Werner & Clark, 2006). In our study, the levels of disturbance were most likely not high enough to cause such a rather long-lasting response, as most individuals returned within a couple of hours to the same field, independent of the repelling method (Figure 3b). Another explanation for the short return times in our study might be linked to the limited availability of suitable feeding sites in our study area so that birds have no choice but to return.

We did not find differences in the behavioural responses towards the three different repelling measures. Our results demonstrate that repelling success and return time do not depend on the type of repelling measure. The sound of a gunshot, which the geese might associate with a serious threat as some of the individuals will have experienced lethal shooting, for example, during migration in Russia or in the non-breeding areas (Heldbjerg et al., 2022), did not cause the individuals to fly longer distances or to reduce their return probability compared with the human approach (Figure 2a,e,f). In crows, shooting was found to have a greater effect on the behaviour compared with non-lethal trapping, with increased flight initiation distances in areas with shooting (Fujioka, 2020). In a study on radio-tracked snow geese, travel distances after lethal repelling (hunting) were longer than after non-lethal disturbance by human approach or vehicles (Béchet et al., 2004), but a study on greylag geese *Anser anser* found no effect of lethal shooting on the flight initiation distance (Månsson, 2017). It seems that the gunshot sounds are not rendering a certain field any more dangerous than plain human approaching. This does not exclude the possibility that the experience of conspecifics getting killed might inflict a stronger reaction in birds, causing them to avoid the area. Future studies should investigate the behavioural responses of tracked geese towards lethal repelling, a management tool which is used in other barnacle goose range countries (e.g. Denmark, Heldbjerg et al., 2022) and has only recently become permitted in Finland.

4.2 | Repeated repelling

We found that treatment number, that is, how many times an individual was already repelled, was included in the best models predicting repelling success and return time (Table 2). Repelling success increased with treatment number, suggesting that individual birds might have learned that certain areas are not safe, or that certain persons (all fieldwork personnel wear reddish/orange vests) are posing a potential threat. Frequent repelling is known to increase the repelling success at a given site also in pink-footed geese *Anser brachyrhynchus* (Simonsen et al., 2016).

We did not find evidence that individual birds habituated towards the repelling measures, which would have been visible as a decrease in repelling success or an increase in return probability with increasing treatment number. Habituation might be more problematic with automatic repelling devices, such as stationary lasers not operated by humans (Blackwell & Bernhardt, 2000; but see Werner & Clark, 2006). Alternatively, the number of repeats or the duration of our study might not have been sufficient to allow for habituation in our study.

Our data do not provide evidence for the assumption that frequent repelling might cause individual geese to use goose fields more frequently. The learning process might take more time for the geese than the few days during which the experiments were conducted. No significant increase in the use of goose fields was also documented from a long-term study in The Netherlands (Koffijberg et al., 2017). Much higher levels of disturbance might be necessary to cause differences in the goose field use. For example, Simonsen et al. (2017) reported that geese had to be repelled at least 5 or 7 times a day to affect the grazing intensity at a given field, whereas the individuals in our study experienced only one to three repelling events per day.

4.3 | Management implications

Following the three target parameters set in the discussion, we cannot recommend one method for all situations—given that (1) no differences in the repelling probabilities were found between the methods, (2) the lowest probabilities to return to the same field were found for human approach and gunshot sound treatments in spring, but (3) the travel distances were lowest after the handheld laser treatment. Thus, our results imply that a combination of methods would be most effective, with the choice of method depending on the circumstances (e.g. light condition, presence of non-target wildlife).

Nevertheless, we found that repelling by handheld laser and gunshot sound are more than twice as fast as by human approach. This confirms a similar study on geese, where <2 min were needed to effectively displace birds with a handheld laser (Clausen et al., 2019). This time difference will reduce costs for working hours by 50%, which is of economic significance if repelling has to be conducted many times a day for several weeks annually. In addition, because the effective range of handheld lasers is considerable, up to several hundred meters, they can be used far away without approaching geese, which will reduce the time investment even more. In combination with the fact that handheld lasers did not perform worse than the more traditional repelling methods in terms of repelling success (Figure 2c–d), we can recommend the use of handheld lasers for repelling, especially in areas where the use of gunshot sounds is problematic, for example, close to human settlements or in areas with sensitive wildlife (as the specificity of the handheld laser is high). However, considering the higher return rates after the repelling with handheld lasers in spring (Figure 3e), certain limits for this technique need to be considered. This might include situations with bright sunlight or very large aggregations of geese.

AUTHOR CONTRIBUTIONS

Toni Laaksonen and Jukka T. Forsman conceived the idea and designed the project with contributions from Wieland Heim and Antti Piironen; Antti Piironen lead and designed the GPS-tagging of geese with contributions from Tuomas Seimola; Wieland Heim, Jukka T. Forsman, Markus Piha, Toni Laaksonen, Antti Piironen and Tuomas Seimola conducted the fieldwork; Wieland Heim and Ramona Julia Heim analysed the data; Wieland Heim led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

ACKNOWLEDGEMENTS

The authors want to thank all landowners allowing us to work on their property and staff involved in the fieldwork, especially Jorma Nurmi, Petri Timonen and Pihla Kortesalmi. The authors also thank the Finnish Ministry of the Environment for funding. Furthermore, the authors want to thank Marc-André Villard and two anonymous reviewers for their comments on the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All satellite tracking data can be publicly viewed at https://satelliitti.laji.fi/ and are available in the Movebank Data Repository https://doi.org/10.5441/001/1.vd7jb526 (Heim et al., 2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Heim, W., Piironen, A., Heim, R. J., Piha, M., Seimola, T., Forsman, J. T., & Laaksonen, T. (2022). Effects of multiple targeted repelling measures on the behaviour of individually tracked birds in an area of increasing human–wildlife conflict. *Journal of Applied Ecology*, *00*, 1–11. https://doi.org/10.1111/1365-2664.14297