ASSESSING SHORT- AND LONG-TERM RESPONSE OF GULLS TO NON-LETHAL HAZING ON AN OFFSHORE ISLAND

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ABSTRACT

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Non-lethal bird hazing techniques are commonly used to protect public health and safety, defend crops, and safeguard the birds themselves. Examples of their use include warding them away from airports, landfills, oil spills, and other avian toxic exposure situations. Herein we examine the efficacy of non-lethal hazing tools for minimizing impacts to Gulls *Larus* spp. prior to a proposed eradication of introduced House Mice *Mus musculus* at the South Farallon Islands, 30 km offshore of the Central California coast. Methods considered for removing mice include the aerial application of rodenticide, which poses an adverse risk to non-target wildlife, including Western Gulls *L. occidentalis.* During a 15-day hazing trial period conducted in late November and early December 2012, we evaluated the effectiveness of a combination of non-lethal wildlife hazing techniques, including biosonics, pyrotechnics, lasers, helicopter, and effigies for temporary reduction in gull attendance. We found that gull numbers continuously decreased during the trial period, achieving 92%–99.7% reduction in abundance during the last four days of hazing, relative to pre-trial counts. Gull attendance remained very low for at least four days after the cessation of hazing, and there was no evidence of habituation. We also compared counts from winter 2012 to counts during the same dates in 2010 and 2011 and concluded that our measures had reduced gull numbers by as much as 98% at the end of the hazing period. Variation in hazing efficacy was best explained by a model that included hazing method, cumulative day of trial, and time of day. Specifically, lasers, pyrotechnics, and techniques that combined auditory and visual stimuli had the greatest hazing efficacy. Our results demonstrate that non-lethal hazing can be highly effective at reducing gull numbers at roost sites in late November and December in central California, indicating substantial reduction in exposure risk during the proposed mouse eradication.

Key words: avian deterrence, habituation, hazing techniques, mouse eradication, non-lethal hazing, South Farallon Islands, Western Gull

INTRODUCTION

Non-lethal hazing of wildlife is an important tool used by resource managers to reduce wildlife damage, decrease interactions with human use, and protect wildlife from harm (Gilsdorf *et al*. 2003, Gorenzal *et al*. 2004). Hazing techniques include a suite of physical, visual, and auditory methods, including biosonic devices that broadcast alarm, distress, or predator calls (Whitford 2008); pyrotechnics that frighten wildlife through a combination of noise, light, and movement (Gorenzal & Salmon 2008); lasers (Blackwell *et al*. 2002, Werner & Clark 2006, Cassidy 2015); visual deterrents, such as kites, balloons, and mylar tape (Seamans *et al*. 2002, Gorenzal & Salmon 2008); effigies, such as models or carcasses of dead birds (Seamans *et al*. 2007); and helicopters (Marsh *et al*. 1991). These methods have been shown to be effective at dissuading birds from landfills (Curtis *et al*. 1995, Baxter & Allan 2006, Cook *et al*. 2008), reservoirs (Mott & Boyd 1995, Ashendorff *et al*. 1997, Golightly 2005), and airports (Washburn *et al*. 2006, Belant & Martin 2011), reducing the impact of geese in urban and rural environments (Smith *et al*. 1999), reducing crop damage by foraging birds (Nemtzov & Galili 2006), and reducing the impact of oil spills on waterbirds (Ronconi *et al*. 2004, Gorenzal *et al*. 2006). Many studies have examined the effectiveness of non-lethal control of wildlife to decrease human-wildlife conflicts (Fall & Jackson 2002, Gilsdorf *et al*. 2002, Cook *et al*. 2008, Baruch-Mordo *et al*. 2013, Castege *et al*. 2016), but relatively few have sought to use deterrence for the protection of wildlife from human actions (Read 1999, Cassidy 2015).

The South Farallon Islands, part of the Farallon Islands National Wildlife Refuge, are globally recognized as an important refuge for a diverse group of wildlife. The islands are used by 13 breeding species of marine birds, five species of pinnipeds, and a high diversity of migratory birds each year (DeSante & Ainley 1980, Ainley & Boekelheide 1990). With more than 350 000 breeding birds (Johns *et al*. 2020), the South Farallon Islands are the largest seabird breeding colony in the contiguous United States, hosting globally important populations of several species, including the Ashy Storm Petrel *Hydrobates homochroa*, Brandt's Cormorant *Urile penicillatus,* and Western Gull Larus occidentalis (Ainley *et al*. 2018, Nur *et al*. 2019, Nur *et al*. 2021).

During the 19th Century, human activity (e.g., seal hunting or seabird egg harvest) on the islands resulted in the introduction of invasive House Mice *Mus musculus*, which have had both direct and indirect negative effects on the unique native ecosystem of the islands (White 1995, United States Fish and Wildlife Service [USFWS] 2019). The USFWS, which manages the Refuge, has proposed eradicating the introduced mice to restore the native island ecosystem, recover declining seabird population numbers, and conserve native wildlife and plants (USFWS 2019).

The preferred alternative for removing mice identified in the final Environmental Impact Statement would require the aerial broadcast of bait pellets containing anticoagulant rodenticide (USFWS 2019). This method has proven effective for removing introduced rodents on many other islands around the world (Howald *et al*. 2007, Keitt *et al*. 2011, Mackay *et al*. 2011, Jones *et al*. 2016, Horn *et al*. 2019) but has a risk of exposure for non-target species (USFWS 2019). Previous studies have indicated that the bait products being considered for mouse eradication (Brodifacoum-25D Conservation) could remain available and palatable to mice and other wildlife for several weeks following application (Fisher *et al*. 2011, USFWS 2019).

The timing of the proposed eradication—during the fall or early winter—is when bird numbers are lowest annually and when breeding activities would not be disrupted (Ainley & Boekelheide 1990, USFWS 2019). Approximately 18 000 (range 10 000–24 600) Western Gulls nest on the islands (Nur *et al*. 2021). Long-term data on seasonal occurrence indicates that numbers of Western Gulls at the islands decline sharply to an annual minimum in September and October before gradually increasing over the remainder of the fall and winter (Penniman *et al*. 1990). Likewise, several species of non-resident, overwintering gulls *Larus* spp. arrive at the islands in the fall and remain present in varying, but relatively low, numbers during this time (DeSante & Ainley 1980, Penniman *et al*. 1990, Richardson *et al*. 2003, Point Blue Conservation Science [Point Blue] unpubl. data). This puts them at risk of lethal exposure to rodenticide through direct ingestion of bait pellets or by scavenging carcasses of poisoned mice.

To evaluate our ability to reduce this risk to gulls, we conducted 15 days of hazing trials during late November and early December 2012, in which we evaluated the effectiveness of a combination of non-lethal wildlife hazing methods including biosonics, pyrotechnics, lasers, helicopter, and effigies for temporarily reducing gull attendance. Our objectives were to (1) evaluate differences in hazing efficacy among the different hazing methods tested; (2) determine the overall efficacy of hazing and how it may have changed during the hazing trial period (e.g., whether gulls exhibited habituation or sensitization to hazing); and (3) quantify the gull population response on the South Farallon Islands to hazing efforts both during and after cessation of hazing.

To fulfill these objectives, we investigated both the immediate behavioral response to hazing treatment (i.e., whether gulls departed in response to a particular hazing treatment) and the gull population response during the trial period (i.e., whether gull numbers changed during the trial period). In addition, we sought to characterize any change in hazing efficacy over time, with particular attention to evidence of habituation (i.e., decline in efficacy over time) or sensitization (i.e., increased efficacy over time). Identifying the time course of habituation, if any, provides important information for practitioners. To fulfill the third objective, assessing population-level response, we first compared gull population counts before, during, and after the 15-day hazing period, up to 27 days after hazing ceased. Second, we compared gull population counts during the period of mid-November to early January in the year of hazing (2012) with gull counts during the same dates in the two years preceding hazing (2010 and 2011).

METHODS

Study area

This study was conducted at the South Farallon Islands (37°42′N, 123°00′W), located 48 km west of San Francisco, California, and 30 km from nearest point of the mainland. The South Farallon Islands are part of the Farallon Islands National Wildlife Refuge and consist of two main islands, Southeast Farallon Island (SEFI) and West End (or Maintop) Island (WEI), as well as several smaller offshore islets and rocks totaling approximately 49 ha (0.49 km^2) (Fig. 1). See Ainley & Boekelheide (1990) and USFWS (2019) for detailed descriptions of the islands. SEFI, the largest island in the Refuge, is the only island having regular human activity and infrastructure. WEI, separated from SEFI by a narrow channel, is part of a federally designated wilderness area (Wilderness Act 1964) and is typically visited only a few times a year to perform biological surveys.

Hazing trials

The hazing trials occurred every day from 29 November to 13 December 2012, inclusive (hereafter "trial period"; Table 1), coinciding with the anticipated timing of the proposed mouse eradication operation (USFWS 2019). This encompassed the period in which we actively conducted trials of individual hazing treatments (hereafter trials). Multiple trials were conducted on any given day, with each trial a distinct event, separated in space and/or time from any other trials. In addition, pre-trial gull counts were conducted during the 10 days prior to the onset of hazing (19–28 November), while post-trial monitoring was conducted 14 December–09 January to determine the recovery of gull population counts at the islands to more typical levels.

A total of 21 different avian hazing techniques were tested, some of which were used in combination, resulting in a total of 29 unique hazing treatments (Table A1, Appendix, available online). The combined treatments tested were: (1) use of two or more different pyrotechnics (pyro); (2) pyrotechnics combined with biosonics or helicopter passes (pyroplus); and (3) helicopter passes combined with the Long Range Acoustic Device (helirad). A description of each hazing treatment is presented in the Appendix.

During the first four days of the trial period, each candidate hazing treatment was tested a minimum of three times. We then identified any candidate treatments that did not work or were wholly ineffective and eliminated those from further trials. Furthermore, some of the 29 treatments were very similar to each other and were pooled for the purpose of analyses (e.g., three different laser treatments were grouped as "laser"). Therefore, after eliminating ineffective treatments and combining similar treatments, we were left with 13 different treatment methods. However, only nine of these treatment methods had a sufficient number of trials (i.e., sample size) to allow statistical analysis (four had eight or fewer trials each). The nine remaining treatments (hereafter principal treatments) were used in 14 or more trials each and constituted over 95% of all trials conducted (469 out of 493 trials).

Hazing was conducted almost continuously at both SEFI and WEI whenever gulls were present during daylight hours within the trial period. Hazing treatments were applied to specific areas where gulls were roosting and continued until all gulls had departed

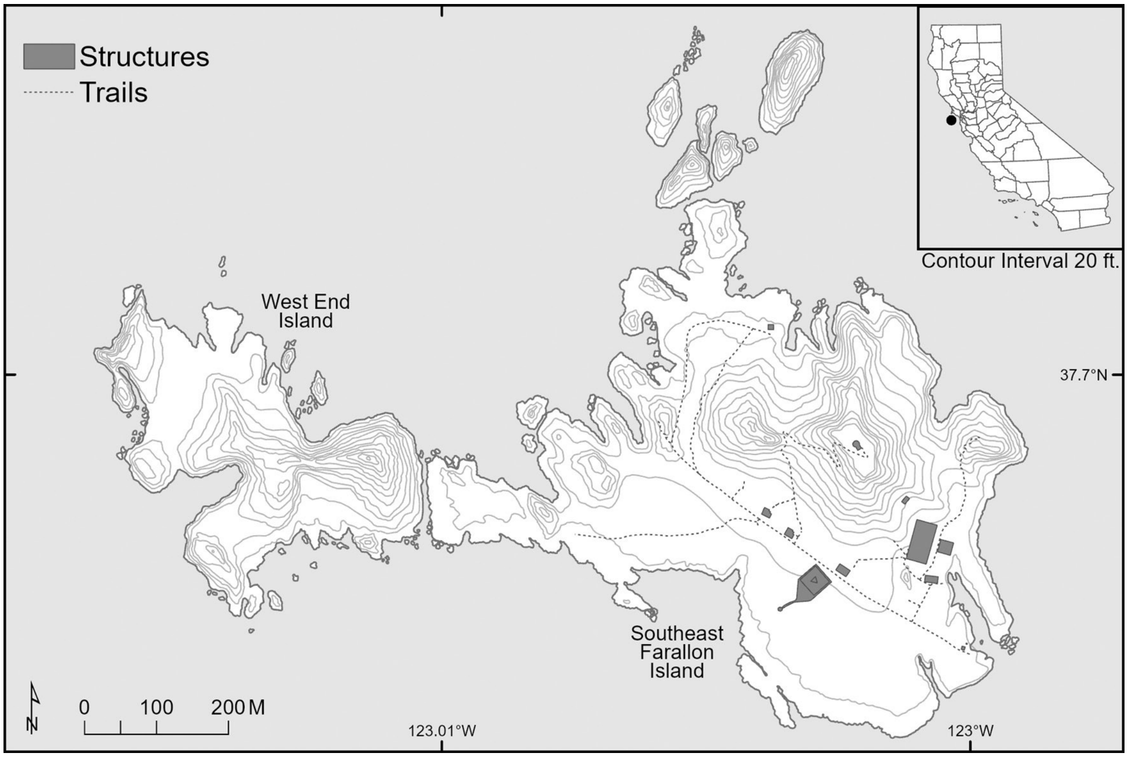

Fig. 1. Map of South Farallon Islands, Farallon Islands National Wildlife Refuge, California, USA. Insert shows position of Farallon Islands in relation to California.

that area. If an individual hazing treatment did not disperse all the gulls in that area, then other (i.e., successive) treatments were applied until all gulls had departed. When deploying combinations of successive treatments, we always deployed the quietest or least aggressive treatments first and added sequentially more aggressive (i.e., louder, more active) methods until the gulls were dispersed. Combinations of successive treatments were analyzed as combined treatments (i.e., the second treatment was not considered independent of the first).

In the last three days of the trial period, effort (number of trials per day) was reduced. Because reduced effort may influence effectiveness of individual trials, we included this covariate in the statistical analysis of hazing efficacy. During this period of reduced effort, gulls were allowed to roost in intertidal or wave-washed areas where bait would not be applied, including some small offshore islets. These areas were treated as temporary local refugia for gulls where they could potentially be allowed to roost during a mouse eradication operation with reduced risk of consuming rodenticide bait.

Throughout the trial period, gulls were only present in a few areas on the islands at a time, and roost locations changed both during the day and between days. To allow a more direct assessment of the impact of specific hazing treatments, the two main islands were divided into 49 discrete sectors. This allowed us to monitor the result of hazing efforts on specific groups of gulls within the targeted sector. Treatments were applied to specific sectors (or sometimes multiple neighboring sectors) where gulls were present, as opposed to being applied to the entire island. A total of three hazing teams were present on the islands (two on SEFI and one on WEI), allowing multiple discrete hazing efforts to occur simultaneously if they were not in close proximity. Individual hazing trials were assumed to be independent of each other if they occurred in different, non-neighboring sectors or at different times during the day.

Gull abundance surveys

Gull surveys were conducted from SEFI daily, at dawn, by experienced ground-based observers between November and January during the winters of 2010/11 and 2011/12, to establish

TABLE 1
Timeline of hazing trials in 2012

Study period	Scope	Duration	Dates
Pre-trial	Assessing baseline numbers of roosting gulls prior to initiation of hazing activities.	10 days	19–28 November 2012
Trial Period	Assessing the efficacy of active hazing operations to reduce gull numbers and evaluate hazing treatments.	15 days	29 November–13 December 2012
Post-trial	Monitoring gull attendance after cessation of hazing activities.	27 days	14 December 2012–09 January 2013

a baseline estimate of the number of gulls present. Comparable surveys were carried out in 2012/13. All SEFI, WEI, and the surrounding islets were visually scanned with binoculars or a scope from multiple observation points to ensure that all visible areas were surveyed. Counts were conducted at dawn to coincide with peak daily gull attendance during late fall–early winter (Point Blue unpubl. data). For this study, all gulls were counted in the survey, regardless of species or roosting location. The reason for this was twofold: (1) greater than 95% of gulls present on the island are Western Gulls during the period of the proposed eradication (Point Blue unpubl. data) and it was too difficult to identify each individual to species during the trials; and (2) all gulls, of any species, would be hazed during the eradication effort to reduce non-target risks. In 2012, these surveys were conducted from 19 November (10 days prior to the initiation of hazing) until 09 January 2013 (27 days after the conclusion of hazing), corresponding to the dates surveyed in 2010/11 and 2011/12.

Assessing gull response to hazing

Throughout the hazing trial period, trained observers recorded the number of gulls present in the targeted area prior to, during, and after trials of the hazing treatment. When a treatment was applied, observers estimated the proportion of gulls present that "flushed" (i.e., took flight) and, for those individuals that flushed, observers noted what proportion of those individuals immediately departed the area, as opposed to circling and returning to the area. It was not practical to precisely count the number of individuals flushing and/or departing. Here we define "efficacy" of a treatment in a given trial as the proportion of gulls present that flushed and departed the area (i.e., the product of the proportion flushing multiplied by the proportion departing among those that flushed). Thus, an efficacy of 1 means all targeted gulls flushed from the roost and moved away from the area; an efficacy of less than 1 would indicate that either some targeted gulls did not flush (i.e., were unaffected by the hazing method) and/or some gulls flushed and then returned to the same roosting area. The efficacy metric was used as the dependent variable for all analyses of principal hazing treatments.

The impact of hazing activities on gull numbers present (i.e., the long-term response) was evaluated in two ways: (1) by examining changes in the daily number of gulls roosting on the island before, during, and after the 15-day hazing trial period (29 November 2012 to 09 January 2013), and (2) by comparing daily counts in 2012/13 to the same calendar dates in 2010/11 and 2011/12.

Statistical analysis

All statistical analyses were conducted with the computer software Stata 17.0 (StataCorp 2021).

To evaluate the short-term response of gulls to hazing, we analyzed the logit-transform of efficacy, i.e., $\ln(p/(1-p))$, where $p = \text{efficacy} + .01$, to avoid undefined logit values. Because efficacy is a proportion varying from 0 to 1, the logit-transformation was needed to ensure that the variance of the dependent variable met the assumptions of the linear model. We fit linear models with respect to the nine principal treatments (Table A1, Appendix), with treatment as a factor. We also included in our analysis the "day" of the hazing trial period, which varied from 1 (first day of hazing, 29 Nov) to 15 (i.e., 13 Dec); hour of the trial, treated as a Table decimal hour, varying from 6.1 to 17.5 (i.e., 06h06 to 17h30); and hazing effort that day (total number of hazing trials on the respective day). We evaluated competing models based on Akaike Information Criterion (AIC) and an *F*-test for each model term (i.e., comparing a model with the term to the same model without the term), considering, as well, quadratic terms for day and hour. We confirmed that residuals were approximately normally-distributed for the preferred model.

We compared treatments with respect to efficacy, while adjusting for the effects of day and hour of trial. Model output, i.e., estimated efficacy by treatment, is illustrated using the margins command, which provides model-based estimates and their 95% confidence intervals (CIs) while adjusting for the effects of day and hour, set at their mean values. Model output was then back-transformed to convert the results obtained from the logit-transformed dataset back to the original scale of the data, in this case a proportion.

To determine how efficacy changed, if at all, during the 15-day hazing trial period, we compared five functional responses. For each response, we indicate the corresponding parametrization with respect to the day of the trial period ("day", which varied from 1 to 15):

i. Linear response over time, i.e., constant increase or decrease in efficacy over time
ii. Increasing but decelerating response, no plateau reached; ln(day)
iii. Asymptotic increase, i.e., initial increase but plateauing at a constant, maximum value of efficacy; inverse-transformation, 1/(day)
iv. Exponential decrease over time, i.e., efficacy exhibits an exponential decay over time, $e^{-\text{day}}$
v. Intermediate maximum, i.e., efficacy increases at first, reaches a maximum, and then decreases over time; quadratic equation

We discriminate among the five functional responses by determining which transformation, if any, of "day" provides the best fit, as determined by AIC.

To evaluate the population response of gulls to hazing, we analyzed the daily dawn population counts, comparing within the year with hazing as well as comparing counts to the two preceding years. The within-year comparison analyzed the number of gulls present at sunrise each day in 2012 before, during, and after the 15-day hazing period. The among-year comparison analyzed the change in the population metric (number of gulls present at sunrise) over the same calendar dates, in each of three years: 2010, 2011, and 2012. In this way, we compared the change in daily gull attendance on the Farallon Islands during the experimental hazing year (2012), with that observed during the non-experimental years (2010 and 2011), using a Before-After-Control-Impact design (McDonald *et al*. 2000).

For the within-year analysis, we analyzed the change in population counts during the hazing and post-hazing periods relative to the mean of the 10-day period pre-hazing, which provided the baseline value. We calculated "percent reduction" for each day during the trial period (days 1–15) and post-hazing (days 16–42). To characterize the population response over time, we fit polynomial curves to the percent change, considering up to fourth-order polynomials for "day." We identified the preferred polynomial based on AIC. Note that percent reduction can be negative if the daily count exceeded the baseline, pre-hazing value.

To provide further insights into the population response over time, we compared the trajectory of daily counts in 2012 to that of 2010 and 2011 for the same range of calendar dates. We first characterized the trajectories in 2010 and 2011 using a lowess smooth, as well as by comparing three models: linear trend, quadratic trend, or a change in trend using change-point analysis (Qian *et al*. 2003). To provide a more direct comparison between the hazing year and the non-hazing years, we calculated a mean count per day for the two non-hazing years and then analyzed the ratio of counts in the non-hazing years to the counts in the hazing year (2012/13), day by day. We present the daily ratios, ln-transformed, together with their 95% CIs, determined using the *margins* command. Ln-transforming the ratios means that a ratio of 1 (abundance is the same in the hazing and non-hazing years) yields a transformed value of zero, a positive value indicates greater abundance in the non-hazing years, and a negative value indicates lesser abundance in the non-hazing years.

The analyses described above, within year and among years, were descriptive. We then developed a statistical model to predict population response to hazing, allowing for effects of hazing effort (measured as the number of trials conducted per day) since greater or lesser effort may influence effectiveness of individual trials. We consider effort for the current day as well as potential effects of hazing effort on previous days, where the effect on the dependent variable does not occur immediately, but rather it lags behind the predictor variable by some number of days (hereafter lags). The dependent variable was ln(count +1) as with the earlier within-year analysis.

We used a two-step approach for model construction. First, we determined the best single predictor of population response while considering hazing effort on the day of the survey as well as each of the five days prior to the survey day. Second, we examined the possible synergistic effect of variable hazing effort over multiple days on hazing efficacy. To do this, we summed hazing effort over one to five days prior to a gull survey. We then evaluated candidate models that included the best single predictor (as determined in the first step) as well the sum of hazing effort over the previous one to five days. For example, in our model terminology, "Lag3" would refer to the hazing effort three days prior to the gull survey whereas "Lag345" would refer to the sum of effort three, four, and five days previously. For both first and second steps, we used AIC to determine the preferred model, which we confirmed with Likelihood Ratios tests.

For the development of predictive models, we fit ARIMA (autoregressive integrated moving average; Chatfield 2004) models using the *arima* command; we tested for first-order autocorrelation, as well as higher order autocorrelations in gull counts between successive days. We also compare results for models with the autocorrelation component to comparable models without autocorrelation.

RESULTS

Hazing efficacy

Efficacy of individual trials varied from 0%–100%. Mean efficacy across all trials was 66.7% (standard deviation [SD] 40.0%; Fig. 2). To evaluate hazing efficacy with respect to hazing treatment, we identified the best statistical model considering the nine principal hazing treatments, as well as three additional factors that potentially affected raw hazing efficacy (day of trial, time of day, and hazing effort). The best statistical model included a significant effect of hazing treatment ($F(8, 454) = 2.37$, $P = 0.017$; Table 2), day of trial (varying from day 1–15; $P < 0.001$), and hour of trial ($P < 0.001$; Table 3). Quadratic terms for day and hour were not significant; the number of trials conducted that day (hazing effort) was also not significant. To account for these factors, we used the estimated efficacy from the best statistical model for all subsequent comparisons of hazing treatments.

Of the nine principal treatments considered, we found that lasers were the most effective hazing treatment with a model-estimated efficacy of 89%, followed by the amplified Bird Gard distress caller (BGA, 83%) and pyrotechnics, either alone or in combination with a secondary hazing treatment (> 80%). Helicopter hazing (49%) and the non-amplified Bird Gard distress caller (55%) were the least effective. Model-estimated hazing efficacy, by treatment, is shown in Figure 3, back-transformed to show proportion.

To characterize the time-dependent nature of hazing efficacy, we compared five functional responses with respect to the day of trial (i.e., linear, quadratic, and three additional transformations, as described in the "Statistical analysis" section). The best statistical model, as determined by AIC, had a positive, linear trend for day of trial while including the effects of hazing treatment (as a factor) and hour of trial (comparison of competing models in Table 4). The preferred model is the same one as in Table 3, which we illustrate in Fig. 4, depicting the linear increase in predicted efficacy in relation to the day of trial.

Population response

Temporal changes in the year of hazing

Gull counts strongly decreased over the entire 15-day hazing trial period, followed by a comparable increase in numbers over the following 18 days (through 31 December 2012; Fig. 5). During the 10-day pre-hazing period, numbers averaged 3610 ± 297 (SD) and did not exhibit a trend ($P > 0.9$ for linear trend). Note: all results reported regarding population response have been back-transformed from ln-transformed analyses. We used the mean for the 10 days prior to hazing (i.e., 3610) as the baseline value to calculate percent reduction in counts during and after hazing. From about 31 December (18 days after the cessation of hazing) until 09 January, numbers no longer increased and were relatively

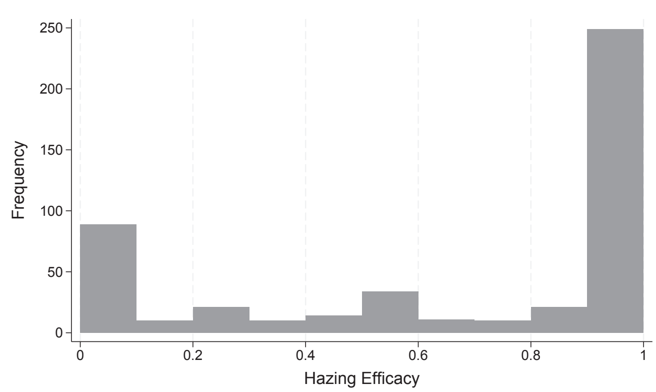

Fig. 2. Frequency distribution of raw hazing efficacy results for the nine principal hazing treatments, binned into 0.1 intervals, $n = 469$.

stable (mean = 3508 ± 507 [SD], with a non-significant linear trend, $P > 0.7$). The mean 10-day post-hazing plateau value was within 2.8% of the mean 10-day pre-hazing counts.

The best polynomial fit characterizing the percent change in counts during the hazing trial period and post-hazing was a fourth-order equation, as determined by AIC (Fig. 6). Percent reduction in counts exceeded 86% on day 7 of hazing and continued to increase subsequently. During the last four days of hazing, the percent reduction in gull counts continued to increase from 91.9% (day 12) to 99.7% (day 15). Substantial reduction in gull counts continued even after the cessation of hazing, especially in the four days after hazing ceased, averaging 90.5% ± 1.40% (SD).

Among-year comparison

We compared the change in population counts over time in the year of hazing (2012/13) with observations during the same time of year (19 November to 09 January) in the two years without any hazing (2010/11 and 2011/12).

In 2010/11, gull counts showed a strong increase from 19 November (day = -9, Fig. 7A) to about 24 December (day = 26) and then were stable from 24 December to 09 January. The AIC-preferred model included a change in trend at day 26: an increasing trend from 19 November to 24 December ($\beta = +0.088 \pm 0.007$, $P < 0.0001$); and a stable trend from 24 December to 09 January ($\beta = +0.002 \pm 0.019$, $P > 0.9$, $R^2 = 0.847$, R^2 adjusted = 0.839; a change point at day 26 was AIC-preferred over all other possible days).

In 2011/12, overall gull counts increased from 21 November (no surveys were completed on 19 or 20 November) to about 14 December (day 16) and were stable thereafter (Fig. 7B). The AIC-preferred model demonstrated a change in trend on 14 December: an increasing trend from 21 November to 14 December ($\beta = +0.068 \pm 0.007$, $P < 0.0001$); and a stable trend from 14 December to 09 January ($\beta = +0.004 \pm 0.006$, $P > 0.5$), $R^2 = 0.769$, R^2 adjusted = 0.756).

Comparing the ratio of gull population counts in the two non-hazing years with gull counts in the hazing year, we found that in the four days prior to the initiation of hazing trials, the ratio was approximately 1 (Fig. 8), and this continued into the first five days of the hazing period. However, from day 6 of hazing (i.e., 04 December) until day 15 (13 December), this ratio increased steeply, reaching 1000:1 on the last day of hazing. Following the cessation of hazing, the ratio decreased until about day 32 (30 December) and was level thereafter.

TABLE 2
Principal hazing treatments included in the analysis and number of trials for each treatment (*n*). The 21 specific treatments (single or combined) that compose the principal treatments are also indicated.[ab]

Principal treatment category	Treatment abbreviation	Specific hazing treatments	*n*
Laser	laser	Penlight Laser Avian Dissuader Aries Phaser	192
Bird Gard Amplified	bga	Bird Gard Super Pro Amplified	45
Pyroplus	pyroplus	Bird Gard with pyrotechnic LRAD with Pyrotechnic Helicopter with Pyrotechnic	31
Pyrotechnic	pyro	Starter pistol cap Banger Screamer Cracker Shell CAPA Rocket Banger with Screamer Screamer with Cracker Screamer with Rocket	48
LRAD	lrad	Long Range Acoustical Device	46
Helirad	helirad	Helicopter with LRAD	34
Wailer	wail	Marine Wailer	14
Bird Gard	bg	Bird Gard Super Pro – 4 speaker Bird Gard Super Pro – Speaker Tower	19
Helicopter	helo	Helicopter	38

[a] Treatments are listed in order of overall mean efficacy.
[b] See Appendix (available on the website) for details on treatments as well as additional treatments that were not included in the analysis.

TABLE 3
Final model of hazing efficacy (logit-transformed) in relation to hazing treatment, day of trial (within the 15-day trial period), and hour of trial[ab]

Model Parameters	Coefficient	Standard error	t	P	95% confidence interval	
Treatment[c]						
Laser	2.147	0.604	3.550	< 0.001	0.960	3.333
Bird Gard Amplified	1.661	0.787	2.110	0.035	0.114	3.208
Pyroplus	1.570	0.810	1.940	0.053	0.022	3.162
Pyrotechnics	1.457	0.724	2.010	0.045	0.036	2.879
LRAD	1.125	0.766	1.470	0.143	0.381	2.631
Helirad	1.048	0.806	1.300	0.194	0.535	2.631
Wailer	1.024	1.106	0.930	0.355	1.150	3.198
Bird Gard	0.249	0.986	0.250	0.801	1.690	2.187
Additional parameters						
Day	0.177	0.050	3.530	< 0.001	0.079	0.276
Hour	0.205	0.040	5.170	< 0.001	0.127	0.284
constant	-3.599	0.845	-4.260	< 0.001	5.259	1.939

[a] The principal treatments are listed in order of overall mean efficacy (higher coefficients) with respect to "helo." Helo was chosen as the base level because it was relatively simple and also the least effective treatment; as a result, all treatment coefficients are positive with respect to helo; hence, no coefficient for helo is shown.
[b] See Table 2 for abbreviations.
[c] The effect of treatment is significant: $F(8, 454) = 2.37$, $P = 0.017$

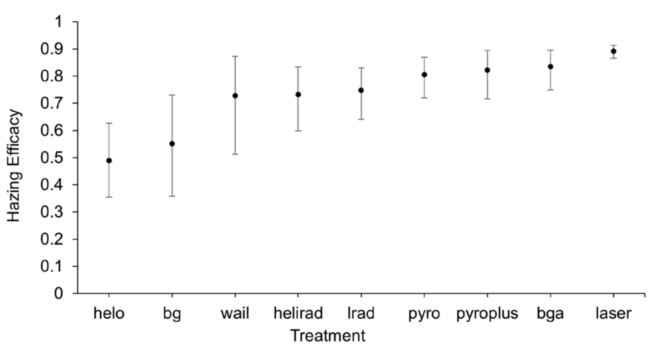

Fig. 3. Model estimates of hazing efficacy by principal treatment, adjusting for effects of hour and day of trial (see Table 3), set at their mean values. Hazing efficacy was back-transformed for illustration. Principal treatment abbreviations are defined as follows: helo = helicopter; bg = Bird Gard; wail = wailer; helirad = helicopter passes combined with long range acoustic device; lrad = long range acoustic device; pyro = pyrotechnic; pyroplus = pyrotechnic combined with biosonic or helicopter passes; bga = Bird Gard amplified; laser = laser. See Appendix (available online) for details on treatments.

Predictive model for population response

We found no significant association between gull counts (ln-transformed) and hazing effort (number of trials) the same day ($P > 0.6$) or the previous day ($P > 0.05$). However, strong associations were evident with the number of trials conducted on days 3 ($r = -0.674$, $P < 0.0001$), 4 ($r = -0.621$, $P < 0.0001$), or 5 ($r = -0.624$, $P < 0.0001$) prior to dawn gull counts such that lower gull counts were correlated with increased hazing effort.

The overall best predictive model included the sum of the number of hazing trials conducted three to five days prior to the dawn gull count (i.e., Lag 345) and a first-order autocorrelation ($r = +0.378$, $P = 0.014$, Table 5). No higher order autocorrelations were significant. This model was highly significant ($P < 0.0001$, Table 5) and provided good predictive ability of the long-term response of gulls to the daily intensity of hazing trials, as demonstrated in Fig. 9 ($R^2 = 0.601$, adjusted $R^2 = 0.589$ for observed ln-counts vs. predicted ln-counts).

TABLE 4
Comparison of Akaike Information Criterion (AIC) values for hazing efficacy

Model	K[a]	Log-likelihood	AIC	ΔAIC
treatment, hour, day - linear	11	-1209.021	2440.042	0
treatment, hour, day - ln-transformed	11	-1210.422	2442.843	2.801
treatment, hour, day - inverse-transformed	11	-1212.466	2446.931	6.889
treatment, hour, day - exponential decay	11	-1213.615	2449.23	9.188
treatment, hour, day - quadratic + linear terms	12	-1208.832	2441.663	1.621

[a] K is the number of parameters.

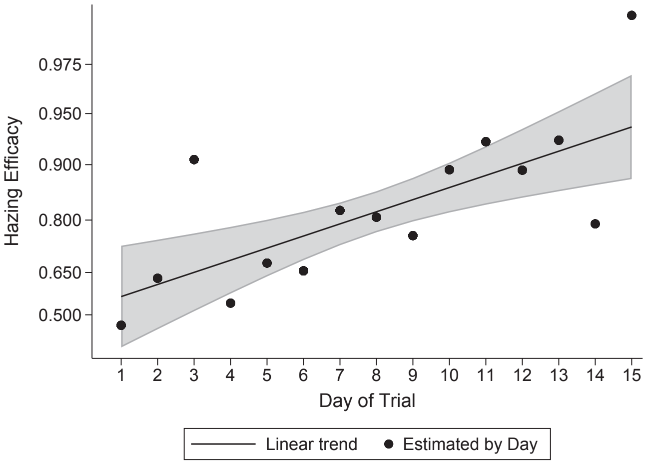

Fig. 4. Model-predicted hazing efficacy in relation to the day of trial, as a linear trend, with 95% confidence intervals (shaded area), adjusting for hour of trial and treatment (Table 3). Also depicted are day-specific estimates of hazing efficacy, adjusting for hour of trial and treatment, with day of trial as a factor (filled circles). Hazing efficacy was logit-transformed for analysis; the y-axis provides the back-transformed values for illustration.

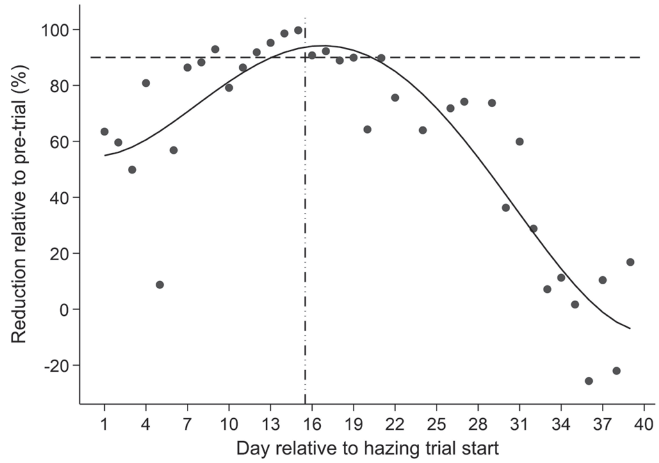

Fig. 6. Percent reduction in daily gull counts relative to pre-trial period (i.e., geometric mean for the 10-day pre-hazing). Day is shown relative to first day of hazing. Polynomial of best fit (fourth-order) is shown by solid line. Percent reduction is < 0 where gull count exceeds baseline value. Vertical dash-dotted line demarcates the boundary between last day of hazing and first day of post-hazing. Horizontal dashed line indicates 90% percent reduction in counts.

DISCUSSION

Overall hazing success

We found that a non-lethal hazing program can be effective for reducing the number of gulls roosting on the South Farallon Islands, thus minimizing the potential risk of gulls becoming exposed to rodenticide during the proposed mouse eradication. Hazing efforts resulted in a high degree of reduction in gull numbers when compared to both pre-trial counts and previous years. We also found no evidence of habituation to hazing treatments during the trial period. Rather, we found a negative association between the number of hazing trials conducted across multiple days and the number of gulls present on the island, such that greater, cumulative

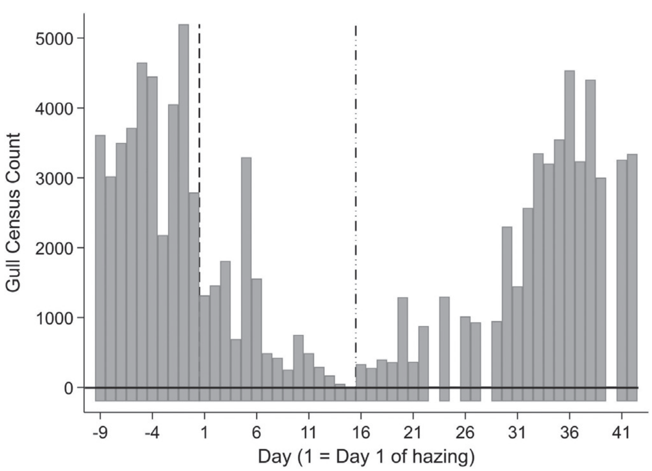

Fig. 5. Number of gulls present on South Farallon Islands, 19 November 2012 to 09 January 2013. Dashed line demarcates the transition from pre-hazing to hazing; dash-dotted line demarcates the transition from hazing to post-hazing. Values of "day" are shown relative to first day of hazing (29 November, day 1).

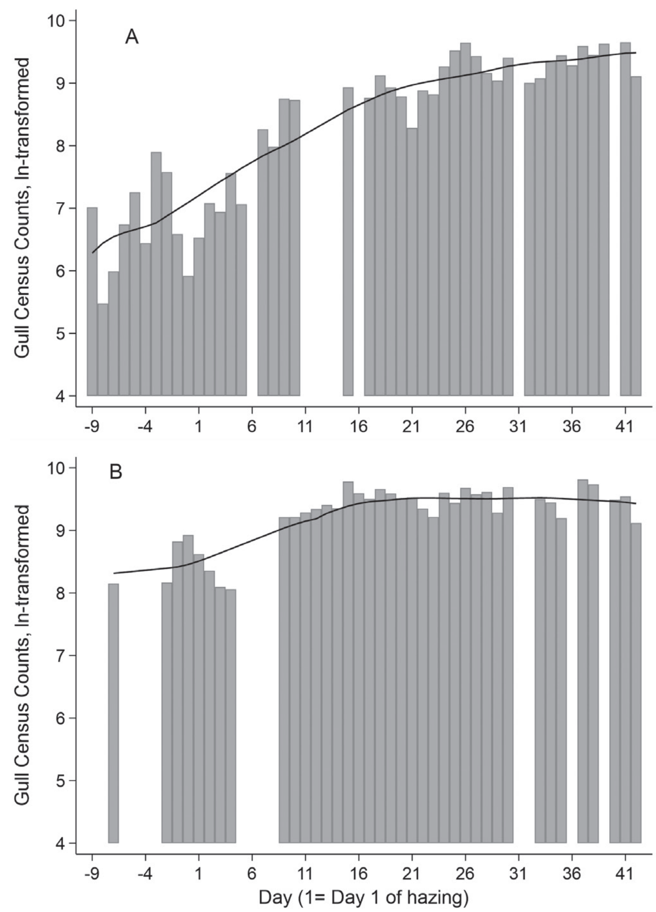

Fig. 7. Population index (counts, ln-transformed) for South Farallon Islands in (A) 2010/11 and (B) 2011/12, by day, for 19 November–09 January in each year. Value of "day" is shown relative to first day of hazing in 2012 (29 November; day 1). Where surveys could not be conducted (due to weather and other logistic constraints), no data are shown. Lowess smooth (smoothing parameter = 0.6) is shown for each year by solid black line.

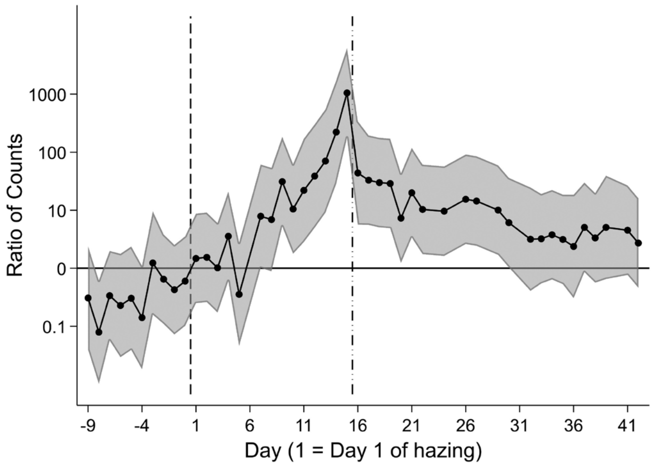

Fig. 8. Ratio of counts in non-hazing years (2010/11, 2011/12) to counts in hazing year (2012/13), by day, depicted on a ln-scale (value labels on y-axis have been back-transformed). Mean values shown, by day, together with 95% confidence intervals (shaded area). Ratios were ln-transformed for analysis. Dashed line demarcates the transition from pre-hazing to hazing; dash-dotted line demarcates the transition from hazing to post-hazing. Values of "day" are shown relative to first day of hazing (29 November, day 1).

hazing efforts led to a greater reduction in gull numbers. This is not only contrary to what would be expected if gulls were becoming habituated (i.e., diminishing returns), but also suggests that gulls were becoming more sensitized to the hazing activities.

Gull hazing efficacy in this study was generally greater than in other similar studies, many of which showed that the initial response to hazing may be great, but that habituation arises quickly leading to a reduction in the effectiveness of dissuasion techniques over time (Stevens *et al*. 2000, Blackwell *et al*. 2002, Baxter & Allan 2006, Gagliardi *et al*. 2006, Soldatini *et al*. 2008). These studies, however, were conducted at locations such as landfills where abundant food resources produced a high motivation for birds to return to the site (Cook *et al*. 2008, Soldatini *et al*. 2008, Lecker *et al*. 2015). This "high feeding motivation" described by Kimball *et al*. (2009) is likely an incentive for gulls to continue to visit the site and adjust to hazing methods. This differs from the Farallones during fall and early winter, when attendance of gulls at the islands is mainly to roost. Western Gulls from the Farallones feed primarily at sea or on the nearby mainland (including landfills; Spear 1988, Shaffer *et al*. 2017), and the island does not serve as a source of food. Therefore, there is little incentive for them to remain at the island during hazing. The use of the islands solely as a roosting site during the winter is not likely a strong enough motivation for gulls to remain in the presence of hazing; alternative roosting locations exist at the North Farallones and on the mainland, both well within the typical daily commuting distance for gulls (Spear 1988, Shaffer *et al*. 2017). During fall and winter, Farallon Western Gulls spend major portions of their time along the mainland coast (Spear 1988; K. Douglas & S. Shaffer, unpubl. data), where the hazed gulls likely moved. Similarly, the timing of the proposed eradication is such that it would occur outside of the breeding season. It is likely that hazing efficacy would be lower during the breeding season when gulls are especially highly territorial (Penniman *et al*. 1990) and so would have a stronger incentive to remain at the colony. Another key difference between this and other studies in which habituation was observed is the use of a large suite of hazing methods (21 specific treatments comprising nine principal methods) combined with frequent variation of treatments. Previous studies have likewise demonstrated the ability to maintain a high level of deterrence for an extended time period, even in the presence of attractive food resources, by using multiple deterrence devices simultaneously and combining the effects of visual and auditory stimuli (Castege *et al*. 2016, Lecker *et al*. 2015). This is similar to our approach, which also combined visual stimuli (e.g., pyrotechnics, lasers, helicopter) with auditory stimuli (e.g., distress calls, explosions) to reduce the predictability of hazing treatments and prevent, or at least delay, habituation.

Temporal population response to hazing

Our results show that there is a cumulative effect of hazing that affects the temporal response of gulls. Even with intense hazing effort, it took several days to achieve a large population response. Once achieved, however, hazing efficacy continued to increase, particularly during the second week of the trial. Furthermore, there was a lasting effect for several days after the cessation of hazing efforts. This result demonstrates that effort, timing, and duration of hazing efforts are important components for successfully reducing gull numbers.

Hazing treatments

Lasers, pyrotechnics, and various combinations of pyrotechnics with additional hazing devices were the most effective at dispersing gulls from their roosts during our study. Lasers and pyrotechnics were often the most effective in previous hazing studies (Gilsdorf *et al*. 2002, Cook *et al*. 2008) and are frequently employed (Gorenzal & Salmon 2008). Lasers were the most effective hazing treatment, on average. They were effective for both clearing roosting gulls and for discouraging gulls from landing. Furthermore, lasers potentially provide a greater degree of accuracy in targeting individuals or groups that are to be dissuaded compared to other methods tested.

TABLE 5
ARIMA model for gull counts (ln-transformed) in relation to number of trials[a]

Variable	Coefficient	Standard error	z	$P > \|z\|$	95% confidence interval	
Number of trials L345[b]	-0.017	0.004	-4.44	< 0.001	0.024	-0.009
AR (1)[c]	0.378	0.155	2.45	0.014	0.075	0.681
constant	7.414	0.330	22.49	< 0.001	6.77	8.06

[a] Model statistics: n = 35; Log likelihood = -41.861; Wald $\chi^2(2)$ = 50.75; $P < 0.0001$
[b] L345 is the sum of the number of trials conducted 3, 4, and 5 days prior to the gull survey.
[c] First-order autoregression (AR (1)) is shown.

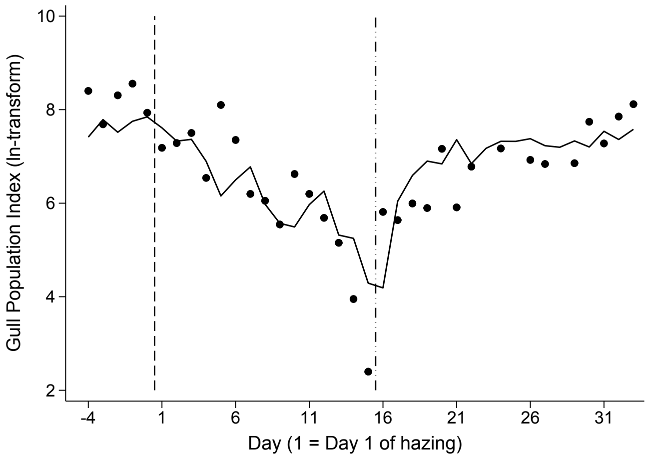

Fig. 9. Daily gull counts on South Farallon Islands (black circles), 2012/13, for the hazing trial period, post-hazing (18 days), and pre-hazing (5 days prior to onset of hazing) together with model-predicted values (solid line; see Table 5). Counts are ln-transformed; dashed line demarcates the transition from pre-hazing to hazing; dash-dotted line demarcates the transition from hazing to post-hazing. Values of "day" are shown relative to first day of hazing (29 November, day 1).

Similar effectiveness has been demonstrated for gulls at airports and reservoirs, where gulls are primarily roosting and do not have a feeding incentive to return, although the type of laser and duration of use may also influence the outcome (Baxter 2007, Lecker *et al*. 2015). However, lasers are not effective for deterrence when there is considerable ambient lighting and were, therefore, not used during daylight hours in this study.

Pyrotechnics, and pyrotechnics combined with other hazing treatments, were likewise highly effective at dissuading gulls from remaining (mean efficacy > 80%). Pyrotechnics are one of the more common methods employed for bird deterrence and combine visual (projectile flying over the roost) and auditory (whistle or bang) stimuli. It is clear from this trial that pyrotechnics are a good choice for wildlife managers when there is a need to deter birds or other wildlife from an area for an extended time and when disturbance to non-target species is not a major concern. Given that pyrotechnics can be both powerful but potentially dangerous to humans and wildlife if not used properly, great care should be exercised when such materials are used as a method for dissuasion. Furthermore, high winds may alter the expected trajectory of the pyrotechnics, leading to greater impacts to non-target wildlife and areas. Where human or wildlife safety is a concern, such as in urban areas or areas with high fire danger, pyrotechnics may be inappropriate.

Biosonic deterrence has been demonstrated to be effective in many applications and is frequently the most effective method employed (Ronconi & St. Clair 2006, Cook *et al*. 2008, Gorenzal & Salmon 2008, Soldatini *et al*. 2008). In the current study, biosonic hazing devices varied in their overall hazing efficacy. Specifically, the amplified Bird Gard units exhibited high efficacy (83%, second highest), whereas the Wailer, LRAD, and unamplified Bird Gard generally had low to intermediate hazing efficacy (50%–75%). Biosonic devices were considerably more effective when combined with another hazing device, such as pyrotechnics (pyroplus) or the helicopter. While the LRAD was not the most effective treatment, it did offer a distinct advantage in the ability to directionally project sounds to better target individual gull roosts while minimizing disturbance to other nearby wildlife.

Finally, we note that helicopter hazing exhibited lower efficacy than we had expected. Previous studies have demonstrated that helicopter activities around seabird colonies can be highly disruptive (Fuller *et al*. 2018, Rojek *et al*. 2007). Furthermore, Coast Guard helicopters (Eurocopter MH-65 Dolphin) that periodically visit the Farallones during winter (for the purpose of Aids-to-Navigation maintenance) have been observed to cause large numbers of gulls to take flight (Point Blue, unpubl. data). There may be several reasons for the low efficacy of helicopters in our trials. First, the Robinson 22 helicopter used during the hazing trial is much smaller and quieter (~78 decibels; EASA 2010) than the Coast Guard helicopters (~118 decibels; Pascioni *et al*. 2020) and may only affect birds that are in close proximity. Second, except for take-off and landing, the helicopter overflight permit required the helicopter to remain a minimum of 800 ft (~245 m) above ground level and to avoid flying directly over the island unless necessary. Flying at this elevation in a relatively quiet helicopter likely reduced its effectiveness as a hazing treatment.

Conclusions, limitations, and management implications

The hazing of gulls from an offshore island during the non-breeding season was found to be both possible and highly effective, if conducted at a high intensity for at least two weeks (the duration of this trial period). Attempting to haze gulls from a coastal roost might be more likely to fail as the gulls would have more choices in the immediate vicinity, and transient gulls might visit. The results of these trials may only apply where gulls or other avian species are hazed at a time when they are visiting the site to roost, as opposed to feed, breed, or for certain other uses, which would be more prevalent along the coast. Hazing efficacy may be dramatically different in those situations or when targeting other species.

It is not possible from this trial to conclusively show that hazing will continue to be as effective over a longer time. A key piece of information for any proposed management action is how long hazing must continue to protect the resource. In the example of the proposed eradication of invasive rodents on the South Farallon Islands, hazing may be necessary for as little as five to eight weeks or more (USFWS 2019). Habituation to hazing treatments was not detected during this trial. Instead, efficacy increased throughout the trial and there was a residual reduction in gull numbers for several days following cessation of hazing activities (Fig. 6), with gull numbers not returning to pre-trial levels until approximately two weeks later. It is possible that habituation could still occur over a prolonged time, especially as it gets closer to the start of the breeding season or if the presence of bait pellets was an attractant to induce gulls to return despite hazing efforts. Although active hazing of gulls only occurred for 15 days in this study, we believe that the trial successfully served as a proof of concept and demonstrated how hazing could be carried out over a longer time span.

Finally, fewer gulls visit the island during times with easterly and southerly wind than during periods with clear weather and northwest winds (Pyle *et al*. 1993). Prolonged periods of either weather type may dramatically alter gull attendance and may impact hazing efficacy or at least the hazing effort needed to dissuade gulls from the islands. During an eradication project, it would be wise to maintain flexibility in timing of implementation to preferentially target periods during which the forecast suggests lower gull attendance.

This study was designed and conducted with two main objectives: to determine the efficacy of dissuading gulls from roosting on the South Farallon Islands for the period of time required to minimize their potential exposure to rodenticide (used for mouse eradication); and to determine the efficacy of a variety of individual hazing tools and techniques to achieve the first goal. These objectives sometimes came into conflict, in which case the overall goal of reducing gull numbers on the islands took precedence over testing particular hazing tools. This resulted in some unavoidable compromises in data quantity for testing individual hazing treatments (e.g., unequal sample sizes, or discarding ineffective treatments early in the trial period). However, we believe that our statistical approach compensates for any shortcomings in data collection and allows for meaningful comparisons between treatment methods.

This study provides valuable information for wildlife managers by demonstrating how prolonged, effective deterrence can be achieved through intensive hazing for a sustained time, using multiple hazing techniques. In addition, this study illustrates differences in the relative effectiveness of hazing treatments on gulls and will empower resource managers to make informed decisions regarding the choice of hazing tools.

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AUTHOR CONTRIBUTIONS

PW and NN led data analysis, writing, and manuscript preparation. PW, RWB, DG, and GJM contributed to project design, data collection, and manuscript review. All authors have agreed to the submission.

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