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Effectiveness of Predator Removal for Enhancing Bird Populations

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Abstract: *Predation pressure on vulnerable bird species has made predator control an important issue for international nature conservation. Predator removal by culling or translocation is controversial, expensive, and time-consuming, and results are often temporary. Thus, it is important to assess its effectiveness from all available evidence. We used explicit systematic review methodology to determine the impact of predator removal on four measurable responses in birds: breeding performance (hatching success and fledging success) and population size (breeding and postbreeding). We used meta-analysis to summarize results from 83 predator removal studies from six continents. We also investigated whether characteristics of the prey, predator species, location, and study methodology explained heterogeneity in effect sizes. Removing predators increased hatching success, fledging success, and breeding populations. Removing all predator species achieved a significantly larger increase in breeding population than removing only a subset. Postbreeding population size was not improved on islands, or overall, but did increase on mainlands. Heterogeneity in effect sizes for the four population parameters was not explained by whether predators were native or introduced; prey were declining, migratory, or game species; or by the study methodology. Effect sizes for fledging success were smaller for ground-nesting birds than those that nest elsewhere, but the difference was not significant. We conclude that current evidence indicates that predator removal is an effective strategy for the conservation of vulnerable bird populations. Nevertheless, the ethical and practical problems associated with predator removal may lead managers to favor alternative, nonlethal solutions. Research is needed to provide and synthesize data to determine whether these are effective management practices for future policies on bird conservation.*

Keywords: bird conservation, culling, evidence-based conservation, hatching success, meta-analysis, predator eradication, systematic review methodology

Efectividad de la Remoción de Depredadores para Incrementar las Poblaciones de Aves

Resumen: *La presión de depredación sobre especies vulnerables de aves ha hecho del control de depredadores un tema importante para la conservación internacional de la naturaleza. La remoción de depredadores por selección o translocación es controvertida, costosa y lenta, y los resultados a menudo son temporales. Por lo tanto, es importante evaluar su efectividad a partir de toda la evidencia disponible. Usamos un método de revisión sistemática para determinar el impacto de la remoción de depredadores sobre cuatro respuestas cuantificables en aves: rendimiento reproductivo (éxito de eclosión y volantones) y tamaño poblacional (pre- y post-reproducción). Utilizamos un meta-análisis para resumir resultados de 83 estudios de remoción de depredadores en seis continentes. También investigamos sí las características de la presa, especie de depredador, localidad y método del estudio explicaban la heterogeneidad en la dimensión de los efectos. La remoción de depredadores incrementó el éxito de eclosión, el éxito de volantones y las poblaciones reproductivas. La remoción de todas las especies de depredadores resultó en un incremento significativamente*

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mayor en la población reproductiva que la remoción de solo un subconjunto. El tamaño de la población post-reproductiva no incrementó en islas, o en general, pero sí incrementó en tierra firme. La heterogeneidad en las dimensiones de los efectos para los cuatro parámetros poblacionales no fue explicada por el origen nativo o introducido de los depredadores; sí las presas eran especies en declinación, migratorias o cinegéticas; o por el método utilizado. Las dimensiones de los efectos para el éxito de volantones fueron menores para especies que anidan sobre el suelo que las que anidan en otros sitios, pero la diferencia no fue significativa. Concluimos que la evidencia actual indica que la remoción de depredadores es una estrategia efectiva para la conservación de poblaciones vulnerables de aves. Sin embargo, los problemas éticos y prácticos asociados con la remoción de depredadores pueden hacer que los gestores prefieran soluciones alternativas no letales. Se requiere investigación para proporcionar y sintetizar datos para determinar sí estas son prácticas de manejo efectivas para futuras políticas para la conservación de aves.

Palabras Clave: conservación basada en evidencias, conservación de aves, erradicación de depredadores, éxito de eclosión, meta-análisis, metodología de revisión sistemática, selección

Introduction

Concern over predation pressure on vulnerable bird species has arisen following two main types of human-mediated environmental change: population growth of native predator species facilitated by scavenging on human waste during lean periods (e.g., Chautan et al. 1998), and non-native predators that have been distributed beyond their natural range, for example, to oceanic islands (e.g., Blackburn et al. 2004; Jones et al. 2008). For bird species that have become endangered through other means, natural predation can become a serious additional problem (e.g., Terborgh 1989; Krebs et al. 1999). In other cases, the wider habitat has become unsuitable, so conservation requires maintaining bird populations at high densities in the few remaining suitable habitat patches, where they can be unusually vulnerable to predation (Hill 1988).

Of the 110 bird species of oceanic islands that have become extinct since the 1600s, introduced predators were responsible for 34% (Groombridge 1992), and 326 threatened species (nearly 30% of the global total) are currently at risk from alien invasive species (Stattersfield et al. 2004). The total removal or reduction of predators—by culling or translocation—for the protection of populations of vulnerable prey species is, therefore, an important issue for nature conservation.

Despite the long history of predator removal in parts of Europe and much of the United States, mainly to increase populations of birds for hunting, it remains a controversial topic. Not only are there animal welfare issues associated with killing predators (Perry & Perry 2008), there are also often high costs, in terms of finance and effort that could potentially be used more effectively on alternative interventions. In addition, conflicts of interest may arise when the predator species itself is of high conservation concern. Both the Hen Harrier (*Circus cyaneus*) and Golden Eagle (*Aquila chrysaetos*) have historically been persecuted in the United Kingdom as predators of game birds, and Hen Harriers are now locally or regionally extinct in many areas because of predator control in the interests of, for example, maximizing harvests of Red Grouse (*Lagopus lagopus scoticus*) (Thirgood et al. 2000). Because predator removal is an emotive and widely practiced method of protecting birds, it is important to evaluate its efficacy from all available evidence.

There have been several reviews of predator removal as a conservation measure for bird species (e.g., Newton 1993, Newton 1998; Côté & Sutherland 1997; Nordström 2003; Gibbons et al. 2007), but only Côté and Sutherland (1997) summarized the evidence quantitatively. From their review of 20 studies they concluded that predator removal serves the interests of game management (to enhance harvestable postbreeding populations) more often than those of conservation managers (who aim to maintain or increase breeding populations of birds). Many new predator-removal measures have been implemented in the 10 years since Côté and Sutherland's review (1997).

Evidence-based conservation (Sutherland et al. 2004) aims to base practice on the collation of evidence. Therefore, we sought to use explicit, systematic review methodology (Pullin & Stewart 2006) to determine the impact of predator removal on bird breeding performance (hatching success and fledging success) and population size (breeding and postbreeding). We also investigated the role of certain factors in explaining some of the heterogeneity in results from studies, including characteristics of prey species, what predators were removed, location, and study design. There are ethical, financial, and practical issues related to predator removal and conservation issues related to removal of native predators, but we do not address these topics here.

Methods

In a systematic review, comprehensive literature searches are conducted to obtain data from published and unpublished research findings. Then, study methodologies are critically appraised and evidence is synthesized to provide empirical answers to predefined research questions

(Pullin & Stewart 2006). This strict methodological and statistical protocol makes a systematic review more robust and powerful than a traditional literature review because it is more comprehensive, minimizes the chance of bias, and improves transparency, repeatability, and reliability (Roberts et al. 2006).

Defining the Research Question

To carry out a systematic review, a specific question must first be defined that includes subject, intervention, and outcome elements, and is answerable in scientific terms (Pullin & Stewart 2006). The question must be clear at the start because it generates the literature search terms and determines relevance criteria. The question also must be practice or policy relevant and be generated by, or in collaboration with, relevant stakeholders because they will implement the interventions. The question of whether predator removal is an effective management strategy was highlighted by stakeholders at a workshop to identify important management or policy issues that could be tackled with an evidence-based approach. Predator control was one of the issues raised because, although it is fairly widely used, it is still a controversial topic. The systematic review question and review protocol were developed from the review by Côté and Sutherland (1997) and by consultation with relevant experts.

Search Strategy

We identified relevant published and unpublished studies by searching multiple electronic databases and the Internet for English language search terms that stemmed from the following 15 words, in the following combinations, that were specific to the review question: (predator) AND (nest OR bird) AND (manage OR control OR remove OR reduction OR exclusion OR trap OR bait OR cage) or (predator) AND (exclosure OR fence OR eradicate OR cull).

In addition, specialist conservation and statutory organization websites were searched for data and for relevant experts and practitioners who were asked for appropriate study results. We also searched bibliographies of articles included in the review and where necessary contacted the first authors of relevant studies to ask for unpublished material and missing data. A more detailed report of the precise methodology used and results are in CEE (2009).

Study Inclusion Criteria

The studies found through our search strategy were assessed for relevance according to an objective list of criteria derived from the review objectives that were formalized in a published protocol (CEE 2009) before the search for articles began. The discrimination process proceeded in two stages. First, all studies found were assessed by their title and abstract, and obviously irrelevant articles were discarded. Articles without sufficient information in the title and abstract to determine relevance were automatically put through to the second stage. At this stage, a random subset of the articles was also assessed for relevance by a second independent reviewer to ensure relevance decisions were justifiable.

Articles that passed the first stage were subjected to the second stage of assessment. We viewed the full text of each article and included it in the systematic review if it provided data on specific bird population parameters in a predator-removal area (treatment) and the study included suitable controls. The controls could be either in an area with no predator removal during the same time period or in the same area before removal began. The four population parameters included were: adult breeding population size (density or count; counted in spring); hatching success of the prey species (percentage); fledging success (number fledged per pair); and postbreeding population size (density or count, counts in autumn including the nonbreeding young of the immediate past season). Predator removal could be by shooting, trapping, or poisoning. We did not include studies that used predator-exclusion methods, such as nest cages and fences; these studies were reviewed separately (CEE 2009).

The quality of data determined whether relevant studies were included in the review. We excluded studies if they had qualitative or quantitative data without comparators or variance measures; if additional management, such as habitat management, was carried out alongside predator removal in the treatment area; and if only artificial nests were monitored. A random subset of the articles viewed at the second stage was assessed for relevance and data quality by a second independent reviewer to ensure the rules laid down in the review protocol were applied consistently.

Data Extraction

Data were extracted from the original studies with a priori rules (see the protocol in CEE [2009]) and summarized in previously designed spreadsheets to minimize bias. Sample sizes, means, and standard deviations for both treatment and control areas were used when provided. Otherwise we calculated them, either from raw data or from the statistics presented in the study. Some studies included data for a community of different prey species and, wherever possible, these species were disaggregated (these separate species data sets within a study are referred to as cases). We extracted separately nonindependent data sets, for example from different sites or years, but aggregated data at a study level to maintain independence. We calculated means across sites or years before effect sizes were generated for each study. To assess the role of certain factors in explaining some of the heterogeneity in results, we also extracted information from each study concerning the prey species (population status, game or nongame, migratory or nonmigratory, ground nesting or not ground nesting); predator species (native or introduced); location (island or mainland [islands defined as areas of land surrounded by sea that are <2000 km^2); and intervention (all or subset of predator species removed). To examine the role of study design in the observed response, we extracted study methodology (time series, simultaneous sites, or site reversal, i.e., where the control area became the predator-removal area and vise versa during the study), number of study sites, and time scale.

Data Synthesis

We explored the effect of predator removal on bird populations through meta-analysis. This requires that the results of each study be summarized on the basis of effect size—an estimate of the response to the treatment (Arnqvist & Wooster 1995; Osenberg et al. 1999). This estimate weights each data set; more weight is given to large studies with precise effect estimates than small studies with imprecise effect estimates. Because response data are continuous, we used Hedges' standardized mean difference (Hedges' *d*) to derive effect sizes, calculated as the treatment effect size relative to the variability observed for each study (Hedges & Olkin 1985). This metric allowed us to combine the different bird abundance parameters, such as density and counts, used in the primary studies (Deeks et al. 2001). We also calculated response ratios for each study, defined as the ratio of the means measured in the experimental to control areas, and used natural logarithms of the ratios to linearize and normalize the metric (Hedges et al. 1999). Sensitivity analyses were carried out to explore the impact of using the two different effect-size metrics (Hedges' *d* and log response ratios) and determine whether they resulted in similar conclusions.

Data were pooled and combined across studies to obtain an overall effect size of the treatment. We calculated this effect size with DerSimonian and Laird's (1986) random effects meta-analysis (Cooper & Hedges 1994). This model allows for the true effect size differing among studies and so is more appropriate than a fixed-effect model for ecological questions that seek to explain between-study heterogeneity (Gurevitch & Hedges 1999). Because random-effects models include between-study variability when there is heterogeneity between studies, the model has wider confidence intervals on its summary effect than a fixed-effect model. We carried out analyses in Stata (version 8.2; Stata Corporation, College Station, Texas) and MetaWin (version 2.1, release 4.8; Rosenberg et al. 2000).

We examined the effect of predator removal by inspecting forest plots of the estimated treatment effects from the studies and their 95% confidence intervals (CI) and by formal tests of homogeneity (Thompson & Sharp 1999). As well as presenting treatment effect sizes, we provide percent success rates compared with the control group. These were calculated by converting the standardized mean difference into the correlation equivalent, which is equal to the success-rate differential between overlapping distributions of scores from two groups and so can be converted into percent success (see conversion table in Lipsey & Wilson 2001).

Publication and other biases were investigated by examining funnel-plot asymmetry (Egger et al. 1997). We calculated failsafe numbers to determine the number of additional (unpublished or missing) studies with a mean effect size of zero needed to reduce significance to $p > 0.05$ (Rosenthal 1979). If the failsafe number is larger than $5n + 10$, where n is the number of observed results, even with some publication bias, it can be considered a reliable estimate of the true effect (Rosenberg et al. 2000).

To explore ecological and methodological heterogeneity between studies, we investigated the relationship between treatment effects (Hedges' *d*) and categorical variables that were defined a priori with random-effects metaregression (univariate and multivariate) in the program Metareg (Stata Corporation) (Sharp 1998). (See "Data Extraction" for the sources of heterogeneity we investigated.) We report only results of significant relationships with covariates, and we lowered alpha to 0.01 to control for type 1 errors. For those variables that showed significant relationships with treatment effects, we used subgroup meta-analysis to explore variation in effect among different studies.

Results

Description of Studies

Of the 6555 articles identified by the search, 427 had sufficient potential relevance for full-text assessment. Ninety six of these articles presented data on 83 predator-removal studies that fulfilled all the inclusion criteria and provided sufficient data to be included in our meta-analysis. In some situations separate articles provided data for different years of the same study. We extracted 175 cases from these, some of which had multiple output measures. Seventy-three percent of the articles were from peer-reviewed publications and 27% were from unpublished sources. Of published and unpublished titles identified during the search, 1.5% contained relevant comparative data. Of the studies included, 29 were conducted in Europe (17 in the United Kingdom), 30 in North America, 20 in Australasia (18 in New Zealand), and four elsewhere.

The 83 predator-removal studies included had relevant outcome measures for a total of 128 bird species. Breeding population size was measured in 51 studies, but only 19 studies measured postbreeding population numbers (see Supporting Information). For comparison, Côté and Sutherland (1997) included 13 studies measuring breeding populations and 10 measuring postbreeding population size. Reproductive success was measured as hatching success in 36 studies and fledging success in 26 studies (Supporting Information); Côté and Sutherland (1997) included 14 studies that reported hatching success. The majority of studies used the percentage of nests found to calculate hatching success (45 out of 50), rather than a daily-exposure method (e.g., Mayfield [1961] method) (nine out of 50). Although percentage of nests found is less robust than a daily-exposure method, we included both types of data.

Only three of the studies presented before-after-control-impact (BACI) data (Slagsvold 1980; Lawrence & Silvy 1995; Ratcliffe et al. 2005). The majority (63%) of studies compared predator-removal areas with control (no predator removal) areas, and in 10 of these 49 studies the removal and control sites were reversed during the study. The remaining 31 studies investigated parameters of bird populations before and after predator removal.

Effectiveness of Predator Removal

Comparing removal areas against control areas with Hedge's *d* as the effect size estimator showed that predator removal had a significant positive effect on hatching and fledging success (Fig. 1). The effect sizes showed an average 77% increase in hatching success and 79% increase in fledging success. (Conversion table of standardized mean difference effect sizes to success rates of the treatment group compared with the control group are from Lipsey and Wilson [2001].) The difference of 60% in postbreeding population size was not significant (Fig. 1), in contrast to the significant positive effect (71% increase) of predator removal on the longer-term measure of breeding population numbers (conversion table from Lipsey & Wilson 2001; Fig. 1).

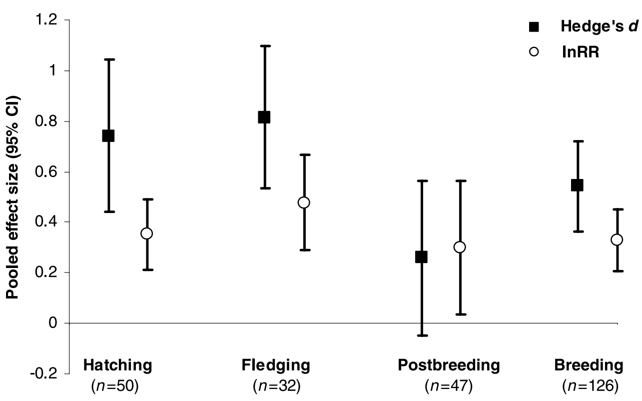

Figure 1. Pooled effect sizes and 95% confidence intervals of predator removal for hatching success, fledging success, postbreeding and breeding population size calculated with Hedge's d *and response ratios (RR) as the effect-size estimators (*n*, sample size).*

Sensitivity analysis with response ratios confirmed that the pooled effect sizes were positive and significant for three of the four variables (hatching success, fledging success, and breeding population numbers), although effect sizes were smaller with less variation for each (Fig. 1). The effect on postbreeding populations was also significantly positive, which contrasted with the nonsignificant result of the meta-analysis with Hedge's *d* (Fig. 1). The effect sizes were, however, both small with lower 95% CIs very close to zero (Fig. 1). The failsafe number for the postbreeding data set was $< 5n+10$, where n is the number of observed results, which means results cannot be considered a reliable estimate of the true effect (Table 1; Rosenberg et al. 2000), as the conflicting sensitivity results suggest.

The funnel plots showed no bias in the reporting of results for fledging success, postbreeding, and breeding populations. The plot for hatching success, however, was consistent with publication bias, which indicated it was easier to publish small studies showing a large positive effect of predator removal (Fig. 2). This bias could have resulted in an overestimate of the effect size, but the three studies with large positive effect sizes had low weights and thus probably did not significantly affect the overall result. Studies with large weights were evenly distributed around the pooled effect size (Fig. 2). The failsafe number for hatching success estimated that 589 nonsignificant studies would be needed to challenge the significance of this conclusion. So even with some publication bias, the result of this analysis can be considered a reliable estimate of the true effect (Rosenberg et al. 2000).

Reasons for Heterogeneity

There was significant heterogeneity in effect sizes between cases for all four population parameters (Table 1) that was related to prey species type and also to intervention for fledging success, postbreeding population numbers, and breeding population numbers. Effect sizes for hatching success, although heterogeneous, were not significantly related to any of the covariates investigated. Heterogeneity was not explained by study methodology (simultaneous site, site reversal, or time series) for any of the parameters.

Whether or not the prey species nested on the ground explained some of the heterogeneity in effect sizes for fledging success (multivariate metaregression: $r = 1.661$ [SE 0.566], $p = 0.003$). Subgroup meta-analysis showed that fledging success in both groups of birds significantly increased with predator removal (Fig. 3a). The increase was not significantly larger for species that do not nest on the ground than for ground-nesting species.

Heterogeneity for the four parameters in response to predator removal was not explained by prey status

Table 1. Heterogeneity between effect sizes calculated with Hedge's *d* and response ratios (RR) as the estimators for four bird population parameters.

Parameter	Number of cases (number of studies)	Estimator	Heterogeneity χ^2 (Q)	Heterogeneity p	Failsafe number
Hatching success	50 (36)	*d*	84.16	0.001	589*
		lnRR	(269.08)	<0.001	552*
Fledging success	32 (26)	*d*	46.24	0.039	351*
		lnRR	37.78	0.187	341*
Postbreeding	47 (19)	*d*	115.39	<0.001	53
		lnRR	(24.60)	0.996	45
Breeding	126 (51)	*d*	301.51	<0.001	1203*
		lnRR	(245.35)	<0.001	1385*

**Failsafe number > 5n + 10 indicates a reliable estimate of the true effect.*

(e.g., breeding populations multivariate metaregression: declining $r = 0.178$ [SE 0.256], $p = 0.486$, increasing $r = 0.242$ [SE 0.275], $p = 0.380$); whether or not the prey was a game species or whether the species was migratory or nonmigratory.

Some of the heterogeneity in effect size for breeding populations was explained by whether all or just a subset of predator species were removed (multivariate: $r = -0.568$, [SE 0.207], $p = 0.006$; univariate: $r = -0.508$ [SE 0.178], $p = 0.004$). In both the cases there was a significant increase in breeding population size, as shown by subgroup meta-analysis, but the effect size was significantly greater when all predators were removed (Fig. 3b). Whether the predator species was native or introduced did not explain any of the heterogeneity for any of the parameters.

Whether predators were removed from a mainland or an island had a significant impact on the effect size for postbreeding populations (univariate: $r = -0.802$ [SE 0.297], $p = 0.007$). Subgroup meta-analysis showed significant increases in postbreeding populations after predator removal on a mainland, whereas removal from islands had a nonsignificant negative effect on postbreeding population size (Fig. 3c).

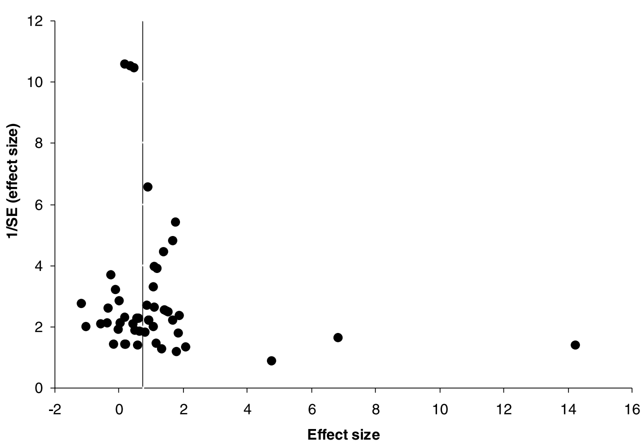

Figure 2. Variation around the pooled effect size of predator removal (dashed line, 0.741) for hatching success calculated with Hedge's d *as the effect-size estimator.*

Discussion

Côté and Sutherland (1997) concluded, on the basis of the evidence available to them, that predator removal was an effective way to increase postbreeding numbers (as required by game managers wishing to harvest a seasonal, temporary surplus of birds, most of which would not survive to breed) but that there was no significant increase in numbers of breeding birds in future seasons (as required by conservation managers for populations of vulnerable birds). Over the last decade, there has been considerable research on the costs and benefits of predator removal, which increased the number of studies we could review from 20 to 83, including an additional 12 studies published before 1996 (Supporting Information). Studies we included in our analyses were from 15 countries across six continents, and 38% of them were carried out on islands. A total of 128 prey species were included, of which 73% were ground nesting and 26% were game species.

Our results show that predator removal can produce significant increases in breeding population numbers and increase hatching and fledging success, as shown previously. There was an average increase of 71% in breeding populations in predator-removal areas compared with control areas. There was no relationship between effect size and prey status, which suggests that predator removal is an effective strategy for management of declining species (42% of cases reviewed here) as well as species that have increasing populations. This conclusion agrees with Holt et al. (2008); Côté and Sutherland

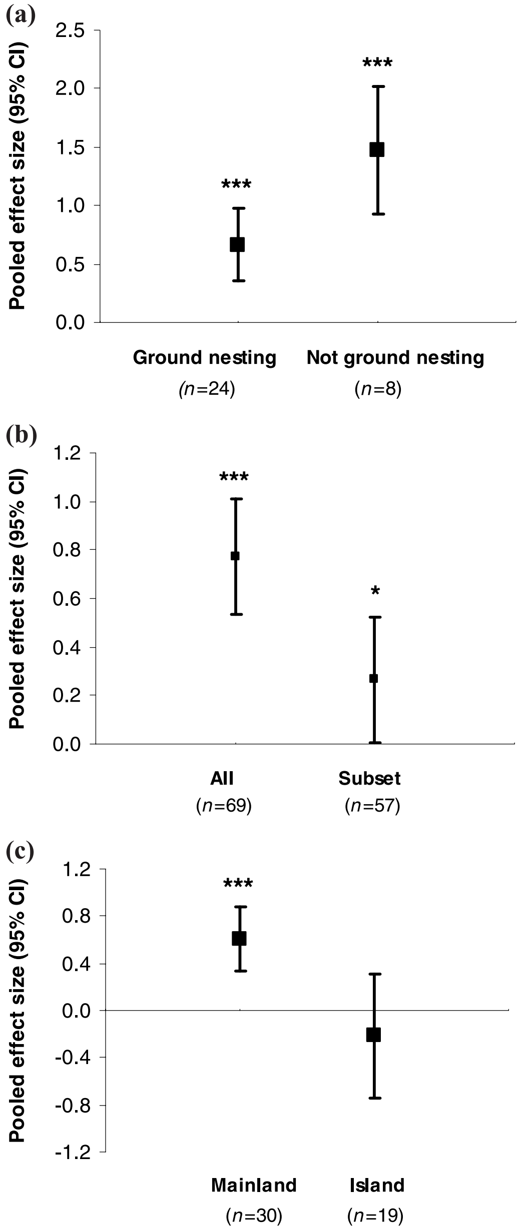

Figure 3. Pooled effect size and 95% confidence intervals of predator removal calculated with Hedge's d *as the effect-size estimator for (a) fledging success of ground-nesting birds and birds that do not nest on the ground, (b) breeding population size when all or just a subset of predators were removed, and (c) postbreeding population size on mainlands and islands. The sample size (*n*) is shown and significant effect sizes are indicated (****$p < 0.001$*; **$p < 0.05$*).*

(1997) found a similar effect size, but wider CIs meant their results were not significant.

A significantly larger increase in breeding population was achieved by removing all predator species rather than just a subset. The same effect has been found in ecological experiments (Trautman et al. 1974; Norrdahl & Korpimäki 2000). Removing all predators excludes mesopredator release and population compensation, where the niche left by one predator species is filled by others (e.g., Greenwood 1986; Parr 1993; Rogers & Caro 1998; Crooks & Soulé 1999). Salo et al. (2007) showed that introduced predators have double the impact of native predators on prey populations, although their result was driven by the impact of introduced predators on the mammal community in Australia. Our effect sizes did not differ between native and introduced species. There are a number of other factors relating to predator ecology and behavior we did not investigate that may alter the effectiveness of predator-removal studies. For example, we did not investigate predator taxa, but Holt et al. (2008) showed that removing mammalian predators was more effective than removing avian predators.

In terms of prey type our results showed that although ground-nesting species are often thought to be most vulnerable to predation, the predation effect size was not higher for them than for other birds. Côté and Sutherland (1995), in their review of 110 studies, also found no difference in the rates of nest predation of ground-nesting versus other bird species. Prey species were disaggregated within studies and analyzed as separate cases because the effect of predator removal is likely to vary for different species. This meant that not all cases were independent in our analyses, which may have affected our results. Nevertheless, due to the substantial sample sizes and the fact that we investigated heterogeneity in effects between studies, it is unlikely to have had a significant effect on the overall results.

Overall, we found that current evidence does not suggest that predator removal could enhance postbreeding populations. This was largely a sampling problem. The failsafe number showed that our sample size was insufficient to ensure that the pooled effect size was a reliable estimate of the true effect for postbreeding populations. Additional studies are therefore required that are well designed (over 30 studies were omitted from our review for lack of a control or spatial or temporal replicates) and ideally long term.

Our results showed there was a significant heterogeneity in the effect sizes for postbreeding populations, some of which was explained by whether the prey populations were on islands or mainlands. Predator removal resulted in increased postbreeding populations on mainlands, but not on islands. This difference helps explain the conflicting overall results between our review and Côté and Sutherland (1997)'s review; that analysis included only two studies from islands out of the 20 included (Marcström et al. 1988; Robertson et al. 1994), whereas 33 of the 83 (40%) studies that we included were from islands. Generalizing results across different ecological situations can be misleading, so we stress how important it is to assess the evidence from similar situations before deciding on interventions to be carried out and to monitor the effects of interventions once they are implemented. On mainlands increased postbreeding populations following predator removal confirms that it is an effective strategy for gamekeepers, who want to achieve a surplus of young birds for shooting in the autumn, whether or not any of them survive to breed. On islands, management is more likely to be for conservation purposes, where a surplus of young is useful only if enough of them join the breeding population.

On the basis of our results, we conclude that predator removal is an effective conservation strategy for enhancing bird populations. This type of management can have long-lasting benefits to prey populations, particularly following the eradication of predators from islands that cannot easily be reinvaded by predators (Veitch 2002; Nordström et al. 2003). In contrast, on mainlands, if predator removal is not continued, any positive effects on prey populations soon disappear as predators move back into the area (e.g., Duebbert & Lokemoen 1980; Tapper et al. 1982; Armstrong et al. 2006). This means predator removal needs to be a long-term management strategy. It also needs to be effective; the majority of studies did not present data on predator densities before and after removal, so we could not examine the success of predator reductions or eliminations in our analyses. Nevertheless, information that was provided indicated the predator reduction or elimination that authors were aiming for was not always achieved (e.g., Guthery & Beasom 1977; Duebbert & Lokemoen 1980; Frey et al. 2003; Meckstroth & Miles 2005).

If resources are limited, removing predators needs to be balanced against investing in habitat creation or improvement. Habitat management can be used either to reduce predation or to increase prey productivity (e.g., by increasing shelter [Schranck 1972; Brickle & Peach 2004], reducing fragmentation and thus the habitat edges used by predators [Chalfoun et al. 2002], increasing food resources [Martin 1992], or removing predator breeding or perch sites [Gibbons et al. 2007]). Nontarget species may also benefit from such habitat management. Predator exclusion could also be considered an alternative to predator removal. Studies investigating interventions such as exclusion fences and nest cages have yielded conflicting results; some found them effective for increasing nest success (e.g., Lagrange et al. 1995; Murphy et al. 2003; Ivan & Murphy 2005), whereas others did not (e.g., Loegering 1992; Mabeé & Estelle 2000; Hansen 2005).

Predator control is not only used as a management strategy for increasing bird numbers, it is also widely used for the protection of mammals. This is particularly the case for the protection of livestock to minimize economic losses. A wide range of predators are controlled to prevent losses of sheep, goats, and cattle for example, including coyotes (*Canis latrans*; e.g., Mitchell et al. 2004; Berger 2006), pumas (*Puma concolor*; Mazzoli et al. 2002) and lions (*Panthera leo*; Patterson et al. 2004). Predators are also controlled to minimize losses to game animals, for example there are concerns over the recolonizing gray wolf (*Canis lupus*) preying on elk (*Cervis elaphus*), white-tailed deer (*Odocoileus virginianus*), and moose (*Alces alces;* Kunkel & Pletscher 1999). Despite the wide use of predator-removal programs, losses to mammalian livestock and game are often unrelated to predator density, and the removal of predators often results in only a short-term reduction in prey losses (Graham et al. 2005). As for predator-removal programs for bird populations, this highlights the long-term nature of this type of management.

Our synthesis of current evidence demonstrates the effectiveness of predator removal for the conservation of bird populations and emphasizes some of the factors that must be considered before removal programs are carried out. Some of the ethical and practical problems associated with predator removal may lead managers to favor alternate, nonlethal solutions, so more research is needed to determine whether they too can result in improved bird populations. Continued synthesis of results from well-designed studies is vital in assessing the effectiveness of management practices for future conservation policy.

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Supporting Information

A table showing the ecological and experimental characteristics and outcomes of the studies included in the meta-analysis (Appendix S1) is available as part of the on-line article. The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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