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IS PREDATOR CONTROL AN EFFECTIVE STRATEGY FOR ENHANCING BIRD POPULATIONS?

Systematic Review

SMITH, R.K., PULLIN, A.S., STEWART, G.B. & SUTHERLAND, W.J.

Conservation Science Group - Department of Zoology - University of Cambridge - Downing Street - Cambridge CB2 3EJ

Correspondence: reb.k.smith@googlemail.com
Telephone: +44 (0)1223 769018

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SYSTEMATIC REVIEW SUMMARY

Background

The control of predators to protect populations of vulnerable bird species is an important nature conservation issue because in recent years predation pressure upon many populations has increased. Predator removal by culling or translocation is controversial, expensive, time-consuming and often temporary and so it is important that the effectiveness of the practice is assessed using available evidence. The aim of the current systematic review is to use explicit systematic review methodology to determine the impact of predator removal on bird breeding performance and population size. We also investigate whether nest predator exclusion using fences or nest-cages is an effective strategy for protecting bird populations, as although both exclusion techniques have been widely used, studies that have tested their effectiveness have shown mixed results.

Objectives

- To assess whether predator control (removal or exclusion) is an effective strategy for enhancing bird populations.
- To assess whether factors relating to the prey species, predator species, location or operational level variables alter the efficacy of predator control programmes in enhancing bird populations.

Search strategy

Multiple electronic databases and the internet were searched using a variety of keywords. Bibliographies, relevant experts and websites were also used to identify relevant studies. Foreign language searches were not carried out.

Selection criteria

- **Subjects -** bird populations; all bird species were included.
- **Intervention -** any method of predator control including shooting, trapping, poison-baiting, exclusion fences and nest-cages.
- **Outcome -** the primary outcome was change in prey species breeding population size (density or count; counted in spring). Secondary outcomes were changes in prey species post-breeding population size (density or count; counts in autumn including the non-breeding young of the immediate past season), hatching success (%) and fledging success (number fledged/pair).
- **Types of Study -** any study providing measures before and after the control of potential predators or comparing predator-control areas to adjacent areas without predator control.

Data collection and analysis

Data were extracted from the original studies and summarised in previously designed spreadsheets to minimise bias. We used DerSimonian and Laird random effects meta-analysis

based on standardised mean difference to examine data on hatching success, fledging success, post-breeding population size and breeding population size. Sensitivity analyses were carried out to explore the impact of using two different effect size metrics, Hedges' standardised mean difference and log response ratios. Meta-regression and sub-group analyses were used to explore ecological and methodological heterogeneity between studies.

Main results

Predator removal resulted in increased hatching success, fledging success and breeding populations. A significantly larger increase in breeding population was achieved by removing all predator species rather than just a subset. Overall, predator removal was not found to enhance post-breeding populations, but evidence indicated that although post-breeding population size was not improved on islands, it did increase on mainlands. Heterogeneity in effect sizes for each of the four population parameters was not explained by whether predators were native or introduced, the prey population was declining, the prey was migratory or a game species, or by study methodology. Effect sizes for fledging success were smaller for ground-nesting birds than those that nest elsewhere, but the difference was not significant.

Nest predator exclusion using either exclusion fences or nest-cages resulted in a significant increase in hatching success. Nest-cages had a larger effect on hatching success than exclusion fences, although this difference was not significant and the sample size for nest-cage studies was small. Heterogeneity in effect sizes was not explained by any of the covariates investigated. There was little evidence to determine whether increased hatching success following nest predator exclusion resulted in increased breeding populations.

Conclusions

Implications for management / policy / conservation
The available evidence suggested that predator control is an effective strategy for the conservation of vulnerable bird populations. Predator removal tended to result in increased breeding populations, which is the main aim of conservation managers. Larger increases were achieved when all predators rather than just a subset were removed. Evidence also suggested that predator removal resulted in increased post-breeding populations on mainlands, but not on islands. Nest predator exclusion using either exclusion fences or nest-cages was found to be an effective conservation strategy for increasing the hatching success of bird populations, but little evidence was available to determine whether this resulted in increased breeding populations. Studies have shown that nest-cages can lead to increased levels of predation on incubating adults and so should be used with caution especially within small populations.

Implications for research
Additional studies are required investigating the effect of predator removal on post-breeding populations, particularly on islands. More evidence is also required on the effectiveness of nest predator exclusion methods, particularly using nest-cages as sample sizes are currently small. Future studies should include the use of independent treatment and controls, replication and ensure effective reporting of data. They should also be undertaken on a wider variety of bird groups in different regions of the world.

It is vital that further studies are carried out to determine whether nest-cages lead to increased mortality of incubating adults and whether the improved hatching success resulting from predator exclusion leads to increased breeding population size.

1. BACKGROUND

A population is defined as 'a group of organisms of the same species occupying a particular space at a particular time' (Krebs 1985). There are four primary population processes that affect population numbers within a given area: natality, mortality, immigration and emigration. Populations increase when natality and immigration outweigh mortality and emigration, and decrease when mortality and emigration outweigh natality and immigration. Predation is one of a number of factors that can cause mortality of birds, it can take place at any stage of life (incubation, pre-fledging, post-fledging or adulthood) and can play an important role in regulating populations. The population growth of native predator species in some areas and the introduction of non-native predators beyond their natural range such as to oceanic islands, has led to increased predation pressure upon many vulnerable species. Research has shown that fauna may be negatively affected and at the extreme pushed to extinction by predation (e.g. O'Connor 1991; Groombridge 1992; Côté & Sutherland 1997). Predation pressure is often set against a background of increasingly fragmented habitats, land-use changes and numerous other human interventions which may increase predation intensity and thus its detrimental effects on populations (e.g. Terborgh 1989; Krebs *et al.* 1999).

The control of predators to protect populations of vulnerable species is an important nature conservation issue. However, despite the long history of predator removal in parts of Europe and much of the USA, 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 both finance and effort, which could potentially be used more effectively on alternative interventions. In addition, conflicts of interests may arise when the predator species itself is of high conservation concern. Because predator removal is an emotive and widely practiced method of protecting birds, it is important to evaluate its efficacy from all available evidence.

To assess the efficiency of predator removal (culling or translocation) as a conservation measure for vulnerable bird species, the results of 20 published studies of predator removal programs were meta-analysed by Côté & Sutherland (1997). Results showed that predator removal had a large, positive effect on hatching success of the prey bird species, with removal areas showing higher hatching success, on average, than 75% of the control areas. Predator removal also increased post-breeding population sizes (i.e. autumn densities). In contrast, the effect of predator removal on breeding population sizes was not significant and studies differed widely in their reported effects. Côté & Sutherland (1997) concluded that predator removal often leads to the goal of game management (to enhance harvestable post-breeding populations) but that it is much less consistent in achieving the usual aim of conservation managers, i.e. to maintain or increase bird breeding populations. In the 10 years since the study took place many new predator control measures (removal and exclusion) have been implemented in an attempt to protect vulnerable nesting birds. The aim of the current systematic review is to use current evidence and explicit systematic review methodology to determine the impact of predator removal on four measurable responses in the birds: bird breeding performance (hatching success and fledging success) and population size (breeding and post-breeding). We also aim to determine whether predator exclusion using fences or nest-cages is an effective strategy for protecting bird populations, particularly ground-nesting species, as although both exclusion techniques have been widely used (Gibbons et al., 2007), only a few studies have tested the effectiveness of these interventions, with mixed results; some showing an increase in breeding success while others suggesting no difference.

The impact of predator control may be dependent on a number of variables. Côté & Sutherland (1997) investigated the effect of the status of the prey species (declining, increasing, or stable), whether the prey species were game or non-game species, whether they were migratory species, whether all or a subset of the predators were removed and whether the study site was mainland or an island. The authors also examined the effect of experimental design (time-series/simultaneous experimental and control sites) on the heterogeneity of outcomes. We investigate the same factors, as well as additional variables including whether the prey species were ground-nesting or not and whether the predators were native or introduced.

We acknowledge that there are ethical, financial and practical issues relating to predator control, and conservation issues relating to removal of native predators, but these topics are not included within this review.

2. OBJECTIVE OF THE REVIEW

2.1 Primary question

Is predator control an effective strategy for enhancing bird populations?

Table 1: Definition of components of the primary systematic review question.

Subject	Intervention	Outcomes	Comparators	Designs
Bird populations	Predator control by: shooting trapping poison-baiting exclusion fences nest cages	Long-term changes in population size (over one year); within season effects on population size (post-breeding), hatching success and fledging success	No predator control	Any studies providing measures before and after implementation of predator control or comparing predator control areas to adjacent or similar areas without predator control

2.2 Secondary questions

Do factors relating to the prey species (increasing/declining, migratory/non-migratory, game/non-game species, ground-nesting/non-ground-nesting), predator species (native/introduced), location (island/mainland) or operational level variables (subset/all predators removed, study design) alter the efficacy of predator control programmes in enhancing bird populations?

3. METHODS

3.1 Question formulation

The question of whether predator control is an effective management strategy was highlighted by stakeholders at a workshop that included the Environment Agency, Forestry Commission, Joint Nature Conservation Committee, National Trust, Natural England, Royal Society for Protection of Birds, Scottish Environment Protection Agency and UKPopNet. The aim of the workshop was to identify important management or policy issues that could be tackled using an evidence-based approach. Predator control was one of the issues raised as 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 & Sutherland (1997) and by consultation with relevant experts.

3.2 Search strategy

Articles included in the review by Côté & Sutherland (1997) were taken as a starting point. Additional relevant published and unpublished articles were identified through computerised searches of the following electronic databases:

1. ISI Web of Knowledge (ISI Web of Science and ISI Proceedings)
2. Science Direct
3. Directory of Open Access Journals (DOAJ)
4. Copac
5. Scopus
6. Index to Theses Online (1970-present)
7. Digital Dissertations Online
8. Agricola
9. Wildlife & Ecology Studies Worldwide
10. www.conservationevidence.com

Searches were carried out using the following English language search terms (* denotes a wildcard used to pick up manage, managed, management, managing for example):

1. predator* AND manag* AND nest*
2. predator* AND manag* AND bird*
3. predator* AND control* AND nest*
4. predator* AND control* AND bird*
5. predator* AND remov* AND nest*
6. predator* AND remov* AND bird*
7. predator* AND reduction AND nest*
8. predator* AND reduction AND bird*
9. predator* AND exclusion AND nest*
10. predator* AND exclusion AND bird*
11. predator* AND trap* AND nest*
12. predator* AND trap* AND bird*
13. predator* AND bait* AND nest*
14. predator* AND bait* AND bird*
15. predator* AND cage* AND nest*
16. predator* AND cage* AND bird*
17. predator* AND exclosure*
18. predat* AND fence*
19. predator* AND eradicat*
20. predator* AND cull*

The search terms were modified where necessary according to the search functionality of the resources.

A web search was carried out using four meta-search engines: AlltheWeb, Google Scholar, Scirus and Dogpile. The first 50 hits (Word and/or PDF documents where they could be separated) from each search were examined for appropriate studies.

The following conservation and statutory organisation websites were also searched:

Birdlife International
British Trust for Ornithology (BTO)
Central Science Laboratory (CSL)
Countryside Council for Wales (CCW)
Department of Agriculture and Rural Development (DARD)
Department of Environment, Food and Rural Affairs (DEFRA)
Department of Environment, Northern Ireland (DOE)
Feral Organisation Australia
Invasive Animals Cooperative Research Centre
Island Conservation
IUCN Invasive Species Specialist Group (IUCN)
Joint Nature Conservation Committee (JNCC)
Natural England (NE)
New Zealand Department of Conservation (DOC)
Royal Society for the Protection of Birds (RSPB)
Scottish Natural Heritage (SNH)
The Game & Wildlife Conservation Trust (previously The Game Conservancy)
The National Trust (NT)

All references retrieved from the computerised databases were exported into a bibliographic software package (Endnote X1, Thomson Reuters, USA) prior to assessment of relevance using inclusion criteria. The bibliographies of all material included at full text were searched for additional relevant articles. Recognised experts and practitioners from the specialist conservation and statutory organization websites and where necessary the first authors of relevant studies were contacted and asked to provide unpublished material or missing data and further recommendations. Foreign language searches were not conducted for this review, but the search identified studies on a global scale all of which were included in the systematic review process.

3.3 Study inclusion criteria

Articles were initially filtered by title and any that were obviously irrelevant excluded. The abstracts of the remaining articles were then examined to assess relevance to the systematic review question. A random subset of the articles was assessed for relevance by a second independent reviewer. Articles were accepted for viewing at full text if it appeared that they contained information pertinent to the review question. In cases where there was insufficient information to make a decision regarding inclusion at title or title and abstract, relevance to the next stage of the review process was assumed. The criteria that articles had to meet for inclusion into the final stage of the systematic review were:

- **Subjects -** bird populations; all bird species were included.
- **Intervention -** any method of predator control including shooting, trapping, poison-baiting, exclusion fences and nest-cages.

- **Outcome -** the primary outcome was change in prey species breeding population size (density or count; counted in spring). Secondary outcomes were changes in prey species post-breeding population size (density or count; counts in autumn including the non-breeding young of the immediate past season), hatching success (%) and fledging success (number fledged/pair).
- **Types of Study -** any study providing measures before and after the control of potential predators or comparing predator-control areas to adjacent areas without predator control.

3.4 Study quality assessment

Articles accepted for viewing at full text were assessed to determine the relevance of reported studies and suitability for meta-analysis. Study data were accepted for meta-analysis when the study fulfilled the above criteria and had appropriate comparator and variance measures. Studies were excluded if they provided only qualitative data or quantitative data without comparators or variance measures. Studies were also excluded if authors reported that potentially confounding, additional management such as habitat management was carried out simultaneously with predator removal in the treatment area, or if artificial nests were monitored.

Quantitative data regarding bird populations with comparators were included but were subject to further appraisal. Study quality assessment is required because well conducted studies have less potential for bias than those that are less robust. Details of the methodology (e.g. study design, number of study sites, timescale) were therefore recorded. Rather than attempting complex standardised recording of design flaws, we dealt with study quality by running sensitivity analyses to compare results from meta-analyses using two different effect size estimators: Hedge's standardised mean difference, which requires sample variances, and response ratio (RR), which can be calculated without knowledge of sample variances (Rosenberg *et al.*, 2000, Adams *et al.*, 1997). Due to time constraints, a random subset of the articles viewed at full text was not assessed for relevance by a second independent reviewer.

3.5 Data extraction strategy

Data were extracted from the original studies using *a priori* rules (see protocol at www.environmentalevidence.org/SR38.html) and summarised in previously designed spreadsheets to minimise bias. Sample sizes, means and standard deviations for both treatment and control areas were used when provided. Otherwise they were either calculated from raw data or from the statistics presented in the study. Some studies included data for a community of different prey species and whenever possible these species were disaggregated (with separate species data sets within a study referred to as "cases"). Non-independent data-sets, for example from different sites or years, were extracted separately, but data were then aggregated at a study level to maintain independence; means were calculated 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 on the prey species (population status, game/non-game, migratory/non-migratory, ground-nesting/non-ground-nesting), predator species (native/introduced), location (island/mainland; islands are defined here as areas of land surrounded by sea that are less than 2000 km^2) and intervention (all/subset of predators removed). To examine any role of the study design on the observed response, details were extracted including study methodology (time-series, simultaneous sites, site reversal), number of study sites and timescale. Information on population status and migratory behaviour, when it was not presented by the author, was obtained from regional references and databases for

Europe (Birdlife International, 1994; 2000; 2004), New Zealand (Marchant, & Higgins, 1990; www.birdlife.org/datazone/species/index.html; www.doc.govt.nz) and the USA (Birds of North America: bna.birds.cornell.edu/bna). European species were defined migratory if they had a migratory status of 3-5 according to Birdlife International categories (2004; 1= resident, 2=partial migrant in Europe, 3=full migrant within Europe, 4=short-distance migrant wintering just outside Europe, 5=long-distant migrant). Scores were altered for specific populations of a species where information was given on distribution maps (Snow & Perrins 1998). Populations of species in other parts of the world were given a migratory status score using the same 5 categories used by Birdlife International (2004) and using distribution maps (bna.birds.cornell.edu/bna).

3.6 Data synthesis

The effect of predator removal on bird populations was explored using meta-analysis. This analysis requires that the results of each study are summarised by the 'effect size'; an estimate of the response to the treatment (Arnqvist & Wooster 1995; Osenberg et al. 1999). Each data set is weighted, with more weight given to large studies with precise effect estimates than small studies with imprecise effect estimates. As response data were continuous we derived effect sizes using Hedges' standardised mean difference, calculated as the treatment effect size relative to the variability observed for each study (Hedges & Olkin 1985). This metric enables the combination of 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; natural logarithms of the ratios were used in analyses to linearise and normalise the metric (Hedges et al. 1999). Sensitivity analyses were carried out to explore the impact of using the two different effect size metrics (Hedges' standardized mean difference and log response ratios) and to determine whether they resulted in similar conclusions.

Data were pooled and combined across studies to obtain an overall effect size of the treatment using DerSimonian and Laird random effects meta-analysis based on standardised mean difference (DerSimonian & Laird 1986; 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). The impact of predator removal was examined by inspection of Forrest plots of the estimated treatment effects from the studies along with their 95% confidence intervals (CI), and by formal tests of homogeneity (Thompson & Sharp 1999). Publication and other biases were investigated by examining funnel plot asymmetry (Egger et al. 1997). Failsafe numbers were calculated 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 cases analysed, even with some publication bias, it can be considered a reliable estimate of the true effect (Rosenberg et al. 2000). Analyses were carried out using Stata version 8.2 (Stata Corporation, USA, 2003) and MetaWin version 2.1 (Release 4.8; Rosenberg et al. 2000).

To explore ecological and methodological heterogeneity between studies, the relationship between treatment effects and categorical variables that were defined *a priori* was investigated using random effects standardised mean difference meta-regression (univariate and multivariate) in Stata using the program Metareg (Sharp 1998). The following potential sources of heterogeneity were investigated: prey species (increasing/decreasing, game/non-game, migratory/non-migratory, ground-nesting/non-ground-nesting), predators removed (all/subset, native/introduced), location (island/mainland), and study design (time-series/simultaneous sites/site reversal). Only results of significant relationships with covariates are reported; alpha was lowered to 0.01 to control for Type 1 errors. The effect of using Bonferroni's correction for multiple-testing was also investigated (α=0.005). For those variables that showed significant relationships with treatment effects, sub-group meta-analysis was used to explore variation in impact amongst different studies.

Methodological limitations of this study are discussed, together with other limitations, in section 5.3.

4. RESULTS

4.1. Predator removal

4.1.1. Description of studies

Searching was completed in May 2008. Of the 6555 articles identified by the search (*n*=6449) and from bibliographies of relevant articles (*n*=106), of which 427 were retained for full text assessment. A random subset of the articles (n=1622; 25%) were assessed for relevance by a second independent reviewer; agreement on inclusion between the reviewers was deemed to be "fair agreement" (Cohen's Kappa test: K=0.49; Cohen 1960). Ninety six of the articles presented data on 83 predator removal studies that measured bird population parameters, fulfilled all the inclusion criteria and provided sufficient data to be included in a meta-analysis (in some situations separate articles provided data for different years of the same study). In total, 175 cases (defined above) were extracted from these, some of which had multiple output measures (Appendix 1). Seventy three percent of the included articles were from peer-reviewed publications and 27% from grey literature.

A number of otherwise relevant studies were excluded because they only provided qualitative data or provided quantitative data with no comparator (*n*=16), no variance measure (*n*=22), output measures other than those included in the meta-analysis (*n*=12), or were literature reviews (*n*=17; Appendix 2). Otherwise relevant studies were also excluded if there were additional management interventions, such as habitat management, at the same time as predator removal (*n*=17; Appendix 2.1; e.g. Smith et al. 1993; Baines 1996; Stoate & Szczur 2001; Tharme et al. 2001; Donlan et al. 2007). Thus, 1.5% of published and unpublished titles identified during the search contained relevant comparative data for predator removal studies. Of the studies included, 29 were conducted in Europe (17 in the UK), 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. Analysis by species was not possible due to small sample sizes. Breeding population size was measured in 51 studies, but only 19 studies measured post-breeding population numbers, i.e. productivity (Appendix 1). For comparison, Côté and Sutherland (1997) included 13 studies measuring breeding populations and 10 measuring post-breeding population size. Reproductive success was measured as hatching success in 36 studies and fledging success in 26 studies (Appendix 1); Côté and Sutherland (1997) included 14 studies reporting hatching success. The majority of studies calculated hatching success as the percentage of nests found (45 out of 50) rather than using a daily exposure method such as the Mayfield method (9 out of 50; Mayfield 1961). Although the first of these methods is less robust, we included both types of data in the review.

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 were a comparison of predator removal areas and control (no predator removal) areas, and in 10 of these 51 studies the removal and control sites were reversed during the study. The remainder of studies investigated bird population parameters before and after predator removal, i.e. as a time-series. The experimental and ecological characteristics of the predator removal studies included are illustrated in Figure 1.

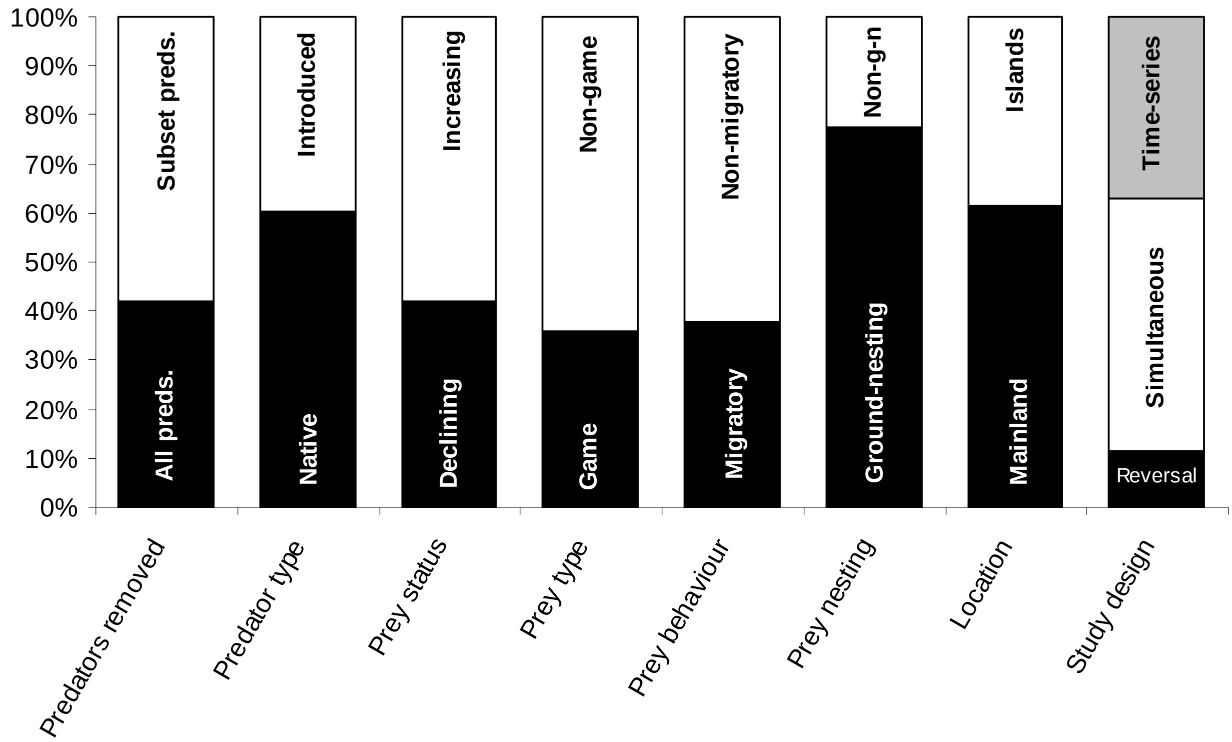

Figure 1. Ecological and experimental characteristics of predator removal studies included in the meta-analysis; proportions of total numbers (86 studies, 175 cases) are shown.

4.1.2. Meta-analysis

Hatching success

Results showed that predator removal had a significant positive effect on hatching success as indicated by a pooled effect size greater than zero and confidence intervals that do not overlap zero (DL SMD=0.741, z=4.81, p<0.001; Figure 2). The range of variation in characteristics of the studies resulted in significant heterogeneity in effect size (χ^2=84.16, *d.f.*=49, p=0.001), which was unexplained by any of the covariates investigated. The funnel plot showed a pattern consistent with publication bias and indicated that it was easier to publish small studies when the results indicated a large positive effect of predator removal (Figure 3). This bias could have resulted in an overestimate of the effect size, however, the three studies with large positive effect sizes had low weights and so are unlikely to have had a significant effect on the overall result; studies with large weights were evenly distributed around the pooled effect size (Figure 3). The failsafe number for hatching success indicated that 589 non-significant studies would be needed to overturn the significant results and so even with some publication bias, the results can be considered a reliable estimate of the true effect (Rosenberg et al. 2000).

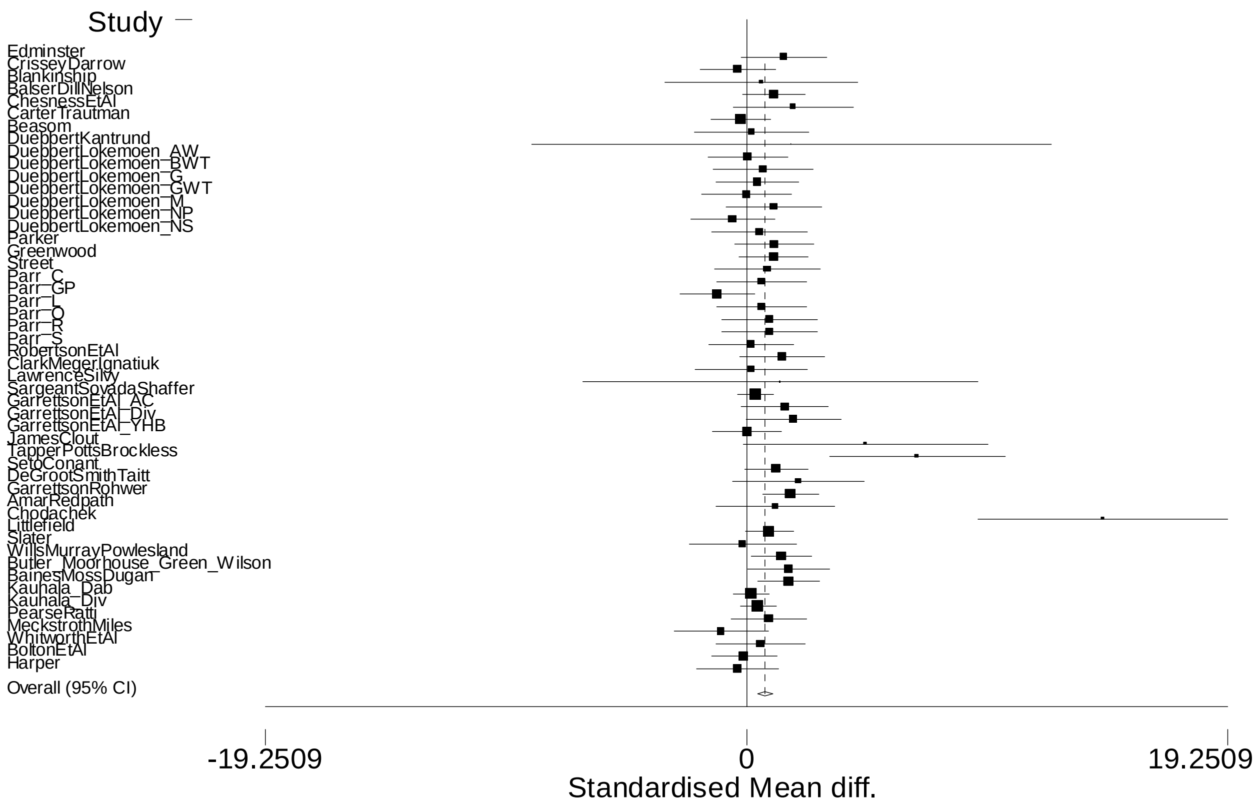

Figure 2. Forrest plot illustrating the variation in effect sizes (solid boxes) for predator removal studies investigating hatching success; Hedge's d was used as the estimator. The solid vertical line represents the line of no effect (0) and the dashed line and open diamond indicate the pooled effect. Box size is related to sample size and error bars are 95% confidence intervals. (Letters after author names indicate species; see Appendix 1).

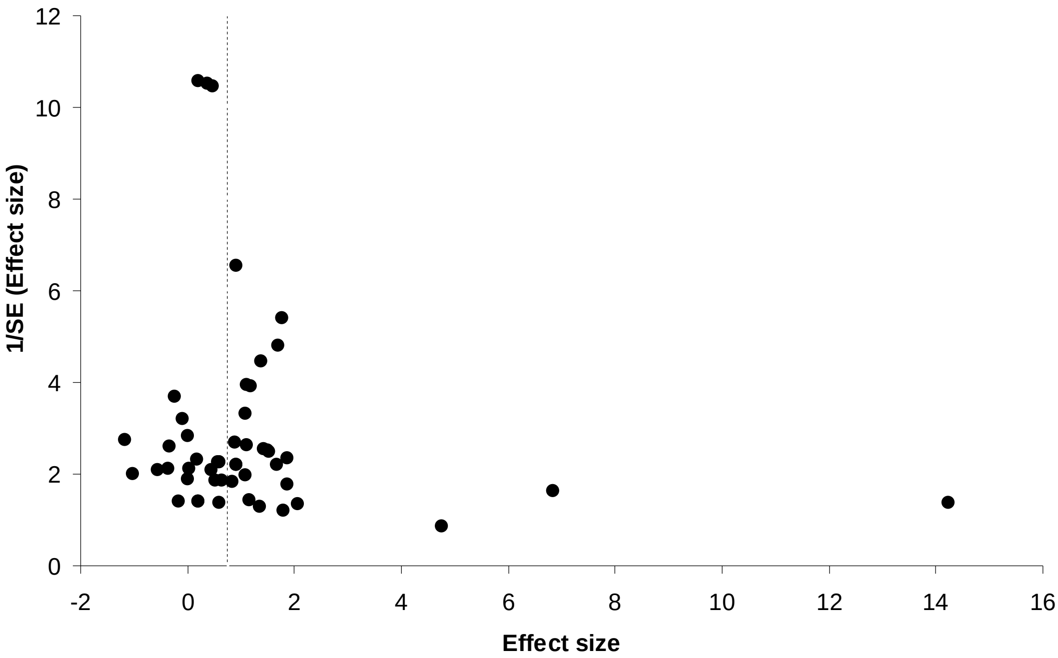

Figure 3. A funnel plot of the variation around the pooled effect size (dashed line = 0.741) predator removal studies investigating hatching success; Hedge's d was used as the effect size estimator.

Fledging success

Results showed that predator removal had a large significant positive effect on fledging success (DL SMD=0.815, z=5.65, *p*<0.001; Figure 4). Funnel plot asymmetry illustrated a pattern consistent with no publication bias (Figure 5) and the failsafe number indicated that 351 non-significant studies would be needed to overturn the significant results.

There was significant heterogeneity in effect sizes (χ^2=46.24, *d.f.*=31, *p*=0.039) and this was partly explained by whether the prey species was ground-nesting or not (multivariate meta-regression: r=1.661, SE=0.566, *p*=0.003). Sub-group meta-analysis indicated that both groups of birds showed significant increase in fledging success with predator removal (Figure 6). The increase was larger for non-ground-nesting than ground-nesting species, but this difference was not significant.

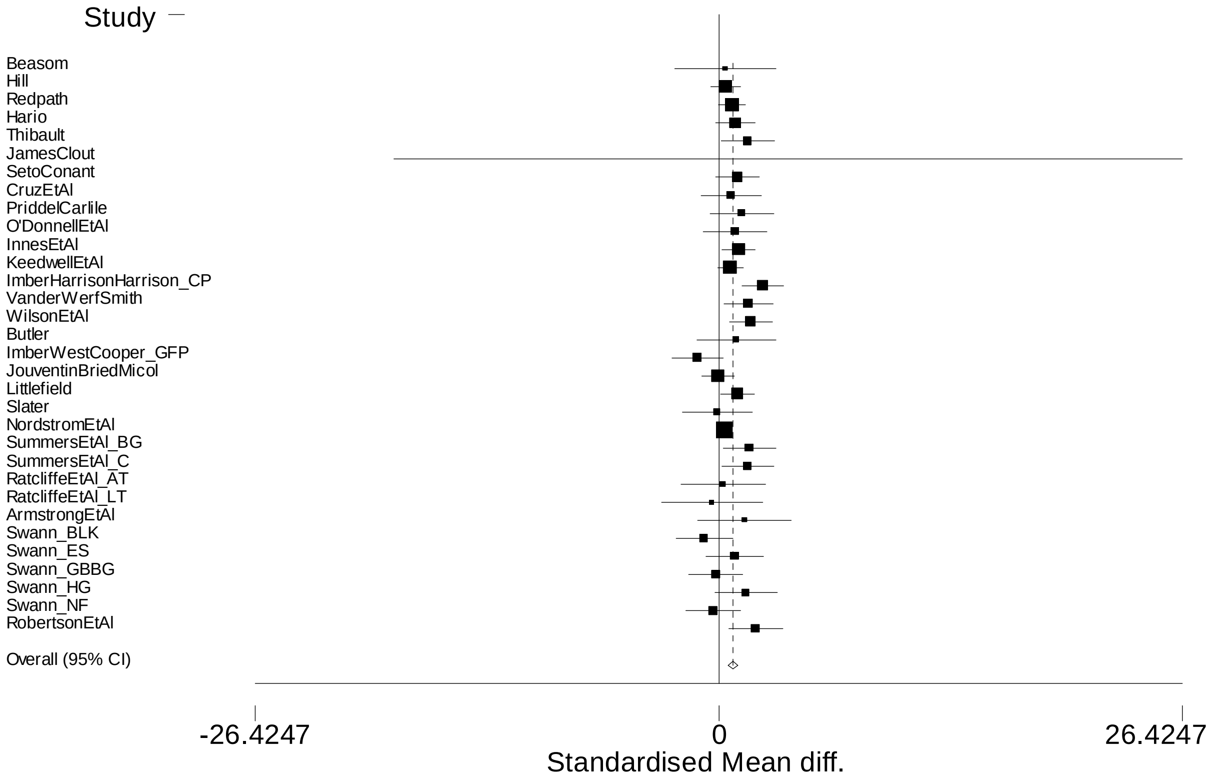

Figure 4. Forrest plot illustrating the variation in effect sizes (solid boxes) for predator removal studies investigating fledging success; Hedge's d was used as the estimator. The solid vertical line represents the line of no effect (0) and the dashed line and open diamond indicate the pooled effect. Box size is related to sample size and error bars are 95% confidence intervals. (Letters after author names indicate species; see Appendix 1).

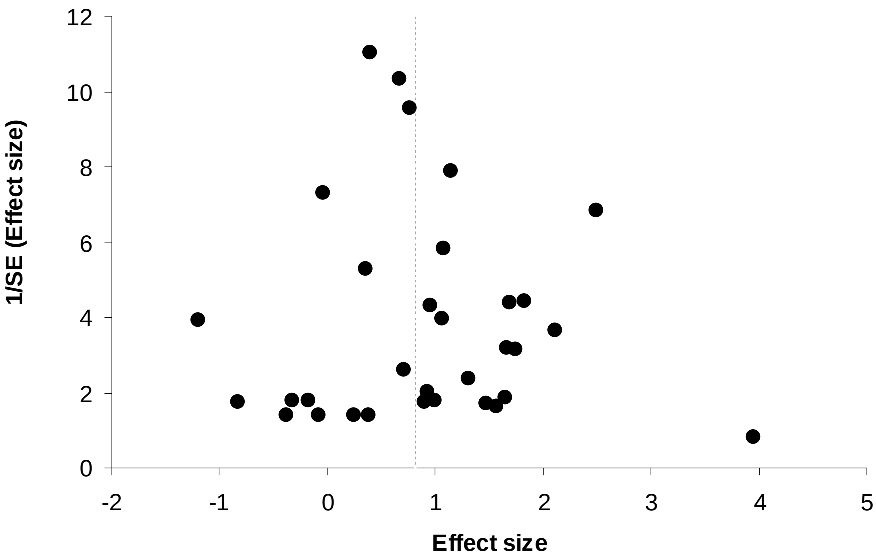

Figure 5. A funnel plot of the variation around the pooled effect size (dashed line = 0.815) for predator removal studies investigating fledging success; Hedge's d was used as the effect size estimator.

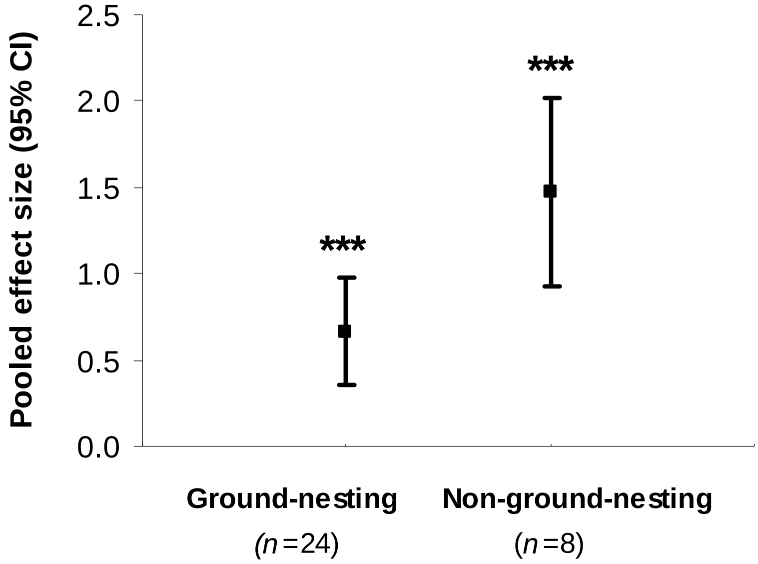

Figure 6. Pooled effect size using Hedge's d as the effect size estimator for fledging success of ground-nesting and non-ground-nesting species. The sample size (*n*) is shown and significant effect sizes are indicated as *** $P<0.001$.

Post-breeding population size

Meta-analysis showed that predator removal had no significant effect on post-breeding population size (DL SMD=0.258, z=1.66, $p=0.097$; Figure 7). The failsafe number was 53, and so less than 5n+10, where n is the number of cases analysed (245) meaning that the results cannot be considered a reliable estimate of the true effect (Rosenberg et al. 2000). Funnel plot asymmetry showed that there was no significant publication bias in the data set (Figure 8).

Results suggested that the range of variation in characteristics of the studies resulted in significant heterogeneity in effect size ($\chi^2=115.39$, *d.f.*=46, $p<0.001$). Multivariate heterogeneity was unexplained, but univariate meta-regression indicated that there was a significant relationship between study effect size and whether the predator removal took place on the mainland or on islands (r= -0.802, SE=0.297, $p=0.007$); this result was not significant after accounting for multiple testing using Bonferroni's correction ($\alpha=0.005$). Sub-group meta-analysis found significant increases in post-breeding populations after predator removal on a mainland, whereas removal from islands had a non-significant negative effect (Figure 9). The fact that the 95% CI do not overlap suggests that there is a significant difference between these two effect sizes.

Sub-group analysis showed that there was no significant difference between effect sizes for post-breeding populations measured using either counts (DL SMD=0.4301, 95% CI =0.0548-0.8054, *n*=38) or density estimates (DL SMD= -0.059, 95% CI = -0.8765-0.7585, *n*=9).

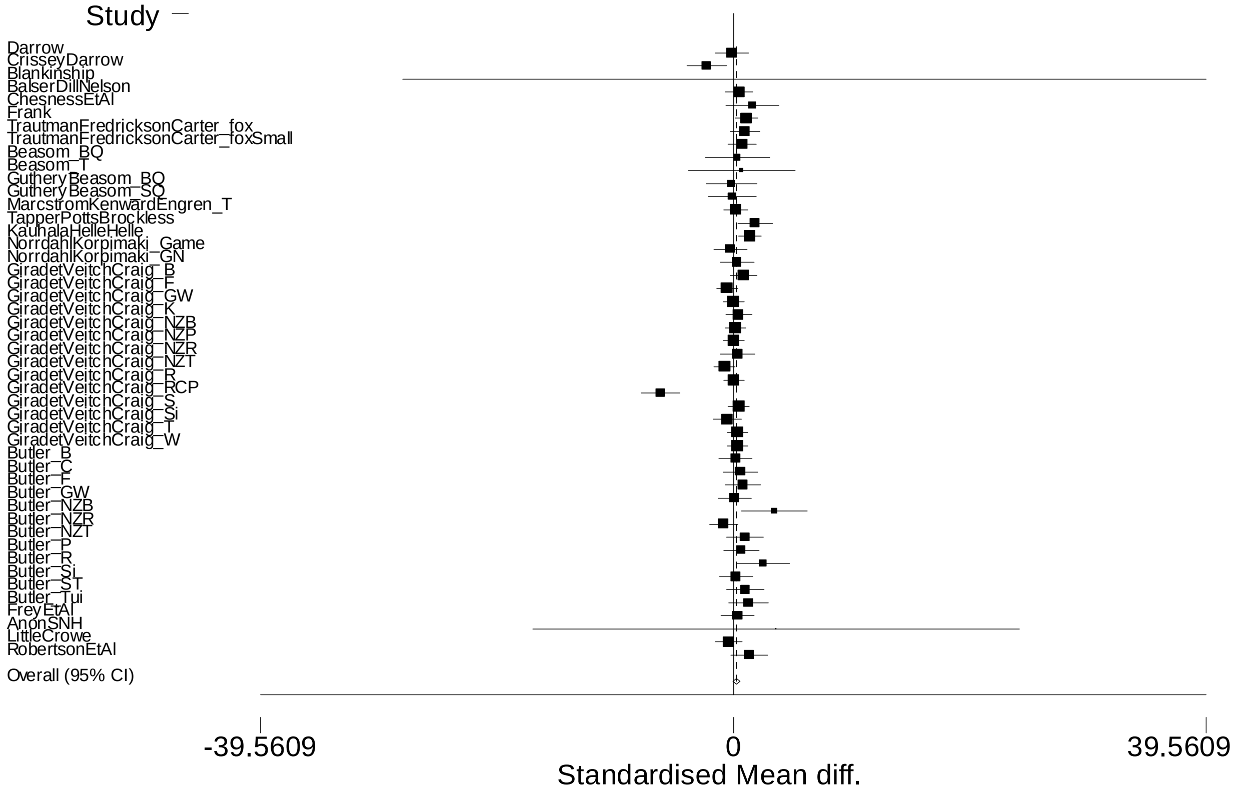

Figure 7. Forrest plot illustrating the variation in effect sizes (solid boxes) for predator removal studies investigating post-breeding populations; Hedge's d was used as the estimator. The solid vertical line represents the line of no effect (0) and the dashed line and open diamond indicate the pooled effect. Box size is related to sample size and error bars are 95% confidence intervals. (Letters after author names indicate species; see Appendix 1).

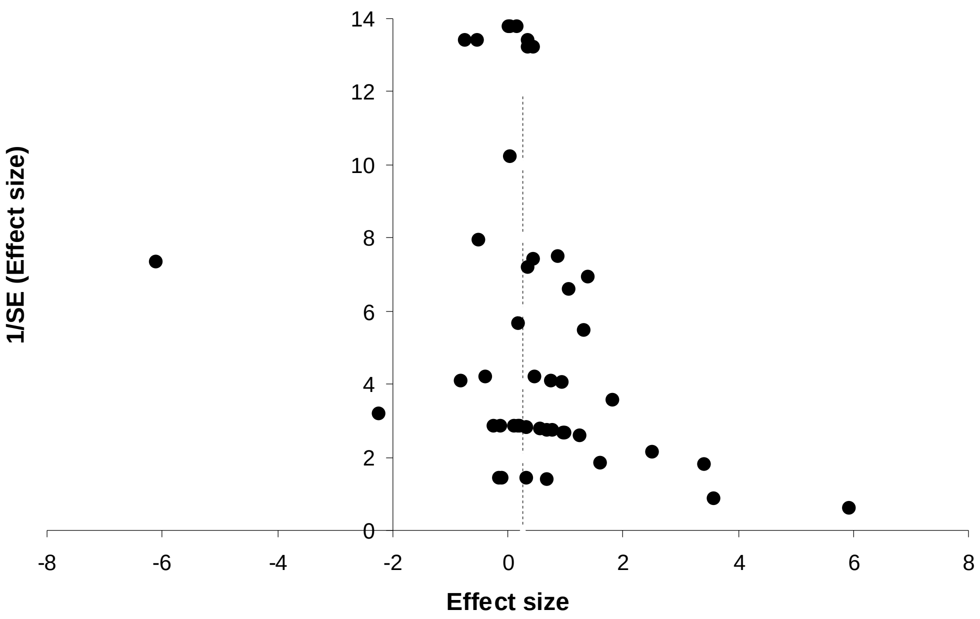

Figure 8. A funnel plot of the variation around the pooled effect size (dashed line = 0.258) for predator removal studies investigating post-breeding populations; Hedge's d was used as the effect size estimator.

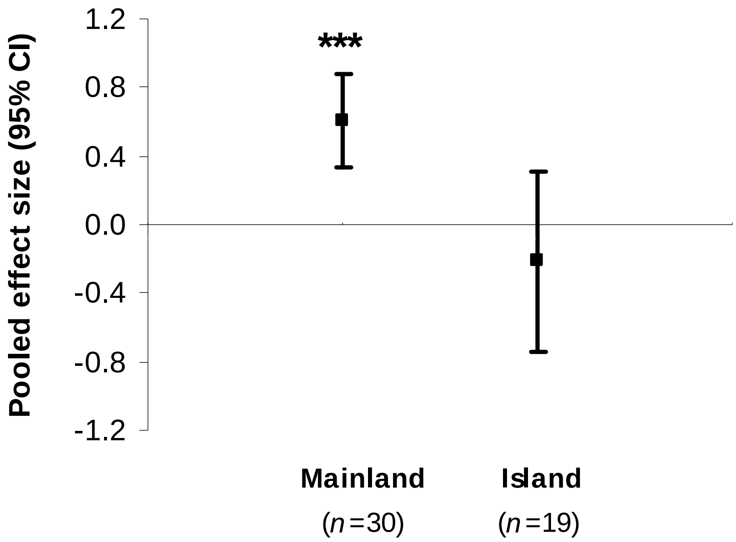

Figure 9. Pooled effect size using Hedge's d as the effect size estimator for post-breeding populations on mainlands and islands. The sample size (*n*) is shown and significant effect sizes are indicated as *** *P*<0.001.

Breeding population size

A meta-analysis of the breeding population studies showed that predator removal resulted in a significant increase in breeding population size (DL SMD=0.542, z=5.98, *p*<0.001; Figure 10). The funnel plot showed a pattern consistent with no publication bias (Figure 11) and the failsafe number indicated that 1203 non-significant studies would be needed to overturn the significant results.

There was significant heterogeneity in effect size (χ^2=301.51, *d.f.*=125, *p*<0.001) and multivariate and univariate meta-regression indicated that there was a significant relationship between study effect size and whether all or a subset of predators were removed (multivariate: *r* = -0.568, SE=0.207, *p*=0.006; univariate: r = -0.508, SE= 0.178, *p*=0.004). The result from multivariate meta-regression was not significant after accounting for multiple testing using Bonferroni's correction (α=0.005). Sub-group meta-analysis indicated that although both sub-groups showed significant increase in breeding populations, the effect size was significantly greater when all predators were removed compared to when just a subset were removed (Figure 12).

Sub-group analysis showed that there was no significant difference between effect sizes for breeding populations measured using either counts (DL SMD=0.2926, 95% CI = -0.009-0.5943, *n*=55) or density estimates (DL SMD=0.6642, 95% CI =0.4298-0.8987, *n*=71).

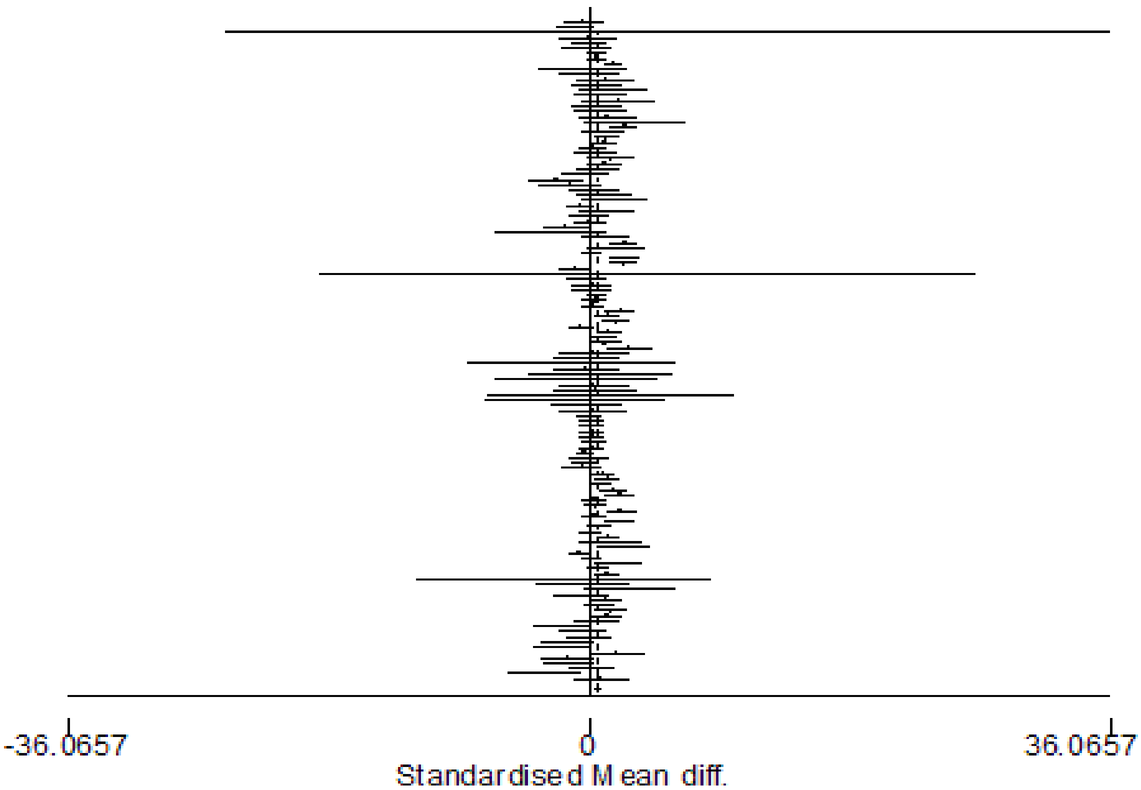

Figure 10. Forrest plot illustrating the variation in effect sizes (solid boxes) for predator removal studies investigating breeding populations; Hedge's d was used as the estimator. The solid vertical line represents the line of no effect (0) and the dashed line indicates the pooled effect. Box size is related to sample size and error bars are 95% confidence intervals.

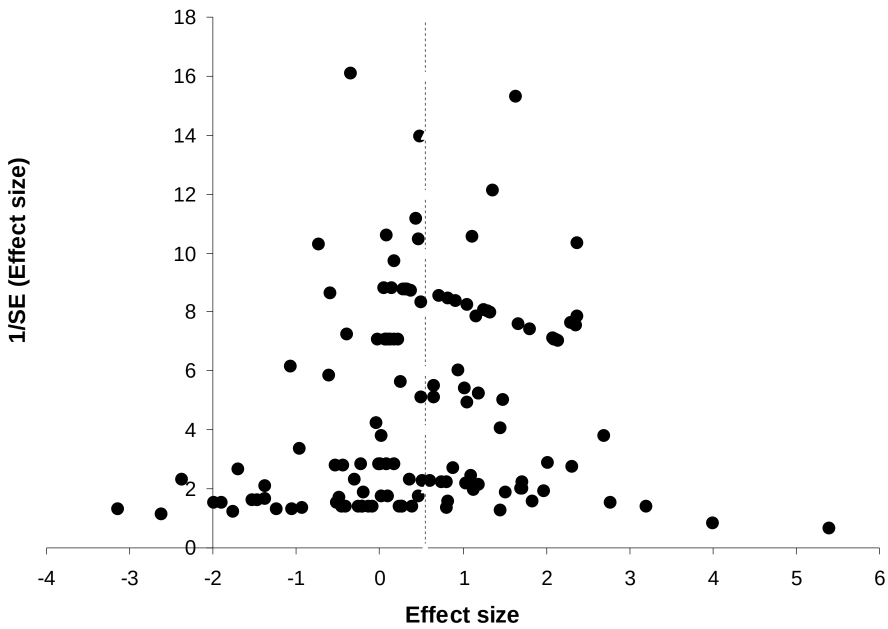

Figure 11. A funnel plot of the variation around the pooled effect size (dashed line = 0.542) for predator removal studies investigating breeding populations; Hedge's d was used as the effect size estimator.

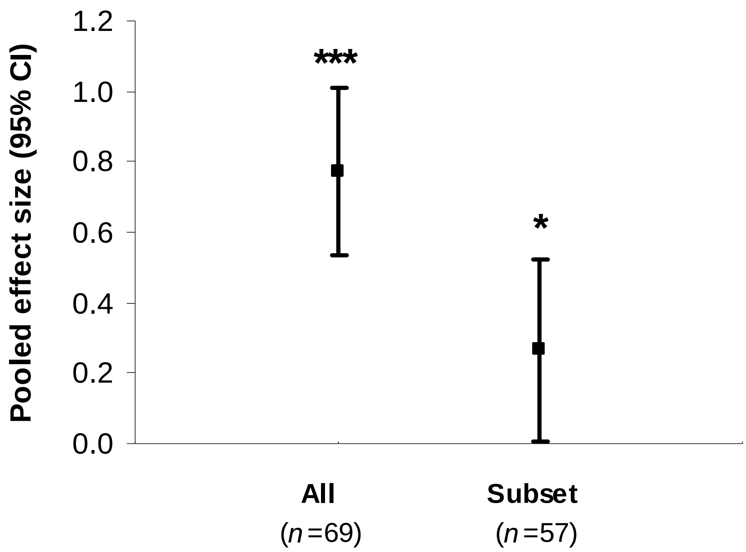

Figure 12. Pooled effect size using Hedge's d as the effect size estimator for breeding population size in studies where all or just a subset of predators were removed. The sample size (*n*) is shown and significant effect sizes are indicated as *** P<0.001, * P<0.05.

Sensitivity analysis

Sensitivity analysis using response ratios confirmed that the pooled effect sizes were positive and significant for hatching success, fledging success and breeding populations, although effect sizes were smaller with less variation for each (Figure 13). For post-breeding populations, results indicated a significant positive effect rather than the non-significant result of the meta-analysis using Hedge's d (Figure 13). The effect sizes were, however, both small with the lower 95%

confidence intervals very close to zero and the post-breeding data set was the one for which the failsafe number suggested that the results cannot be considered a reliable estimate of the true effect (see '*Post-breeding population size*' section above), as this sensitivity analysis suggests.

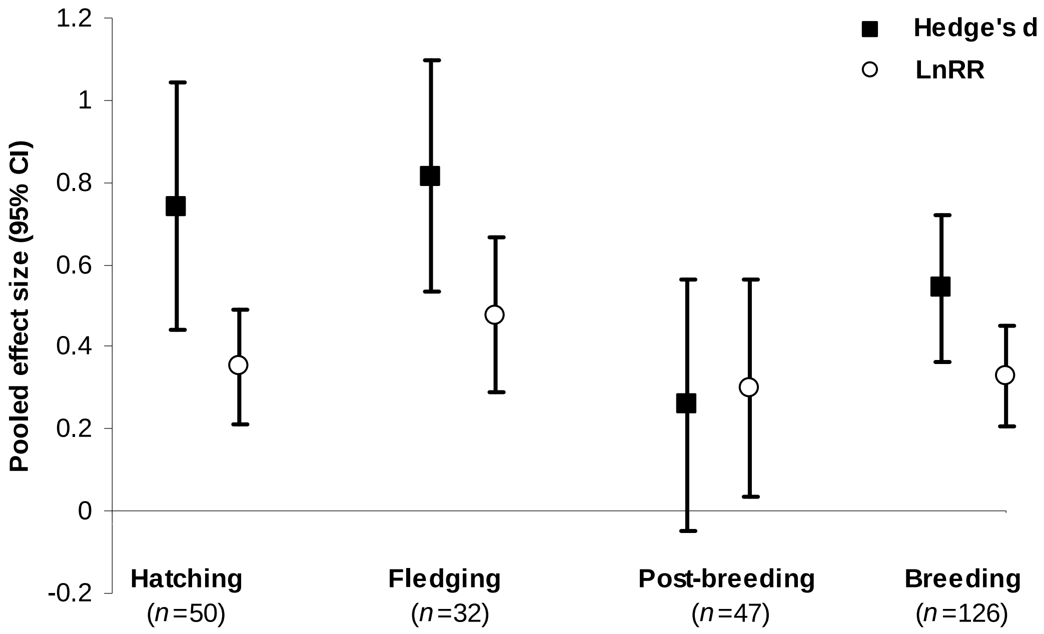

Figure 13. Pooled effect sizes and 95% confidence intervals for hatching success, fledging success, post-breeding and breeding population size using Hedge's d and response ratios (RR) as the effect size estimators. Sample sizes (*n*) are also shown in parentheses.

Comparison to results from Côté & Sutherland (1997)

We were able to replicate the results of Côté & Sutherland (1997) in meta-analyses of the same studies using Hedge's d as the effect size estimator (Table 2). There were small variations in values due to rounding differences and gaps in data reporting in the original article. We increased the number of studies reviewed from 20 to 83, which included 12 additional studies published before 1996. There was little change in the effect size for hatching success with the increase in sample size from 14 to 50, but the 95% intervals were now slightly smaller (Figure 14). The increase in sample size for post-breeding populations (from 12 to 47) resulted in a smaller, non-significant effect size (Figure 14).

The magnitude of the effect for breeding populations was only slightly larger than in Côté and Sutherland's review, but the confidence intervals were substantially smaller and no longer included zero (Figure 14). This indicated that in contrast to Côté and Sutherland's conclusions, evidence now suggested that predator removal resulted in a significant increase in breeding populations.

Table 2. Results of meta-analyses of effect sizes from Côté & Sutherland (1997) and for the same data set re-analysed using Hedge's d as the estimators. * failsafe number > 5*n*+10 indicating a reliable estimate of the true effect.

Model	No. cases (No. studies)	Pooled effects				Heterogeneity		Fail safe no.
		Effect size	95% CI	*z*	*p*	χ^2 *(Q)*	*p*	*n*
Hatching success								
C & S results	14 (14)	0.676	0.300-1.050			(18.39)	0.120	
C & S dataset	13 (13)	0.584	0.158-1.010	2.69	0.007	12.53	0.404	37
Post-breeding population								
C & S results	12 (10)	0.953	0.547-1.359			(16.92)	0.090	
C & S dataset	12 (10)	0.764	0.351-1.177	3.62	<0.001	6.89	0.808	69*
Breeding population								
C & S results	14 (13)	0.339	-0.022-0.700			(25.13)	0.02	
C & S dataset	14 (13)	0.428	-0.149-1.005	1.46	0.146	27.73	0.01	5

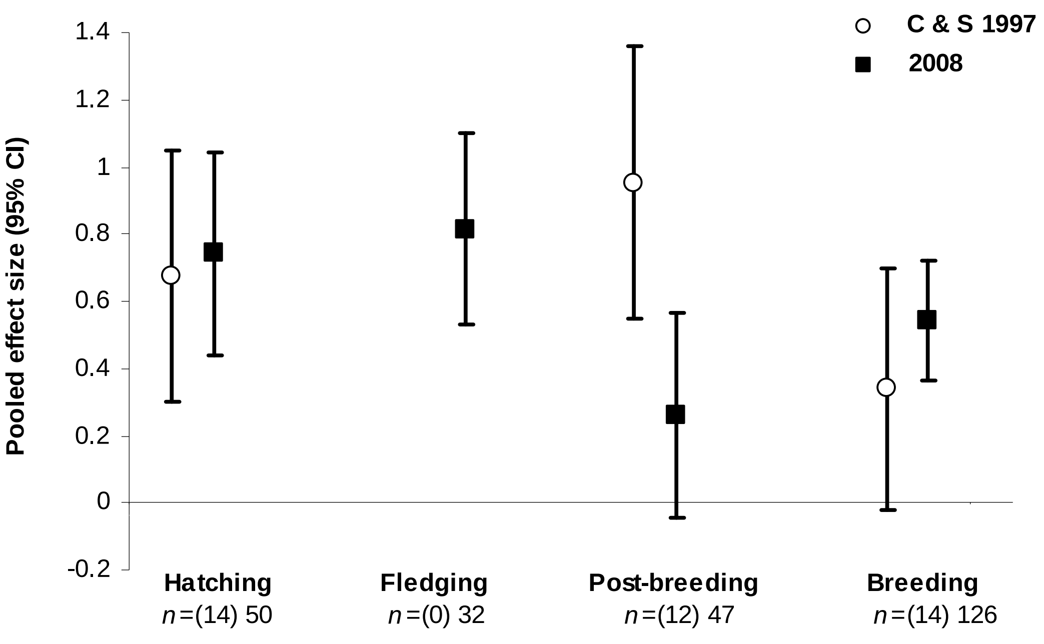

Figure 14. Comparing pooled effect sizes and 95% confidence intervals for hatching success, fledging success, post-breeding and breeding population size from Côté & Sutherland (1997) and current evidence using Hedge's d as the effect size estimator. Sample sizes are shown with those for Côté & Sutherland (1997) in parentheses.

4.2. Predator exclusion

4.2.1. Description of studies

A total of 50 of the 6555 articles identified in the search were retained for full text assessment. Twenty two of the articles presented data on 16 nest predator exclusion studies that measured hatching success, fulfilled the inclusion criteria and provided sufficient data to allow inclusion in a meta-analysis. Twenty cases were extracted from these articles (Appendix 3). Fifteen of the studies were carried out in the USA and one in Scotland, only two were carried out on islands (Jackson 2001; Anon. 2006). A number of otherwise relevant studies were excluded because they only provided qualitative data, quantitative data with no comparator (Deblinger et al. 1992; Wellicome et al. 1997; Cowardin et al. 1998; Gulickx et al. 2007; Morrison and Gurney 2007), quantitative data without variance measures or an output measure other than hatching success (Appendix 4). Otherwise relevant studies were also excluded if there were additional management interventions such as habitat management (Smith et al. 1993; Koenen et al 1996; Neuman et al. 2004).

The 16 nest predator exclusion studies provided hatching success data for seven species: blue-winged teal (*Anas discors*), dunlin (*Calidris alpina*), killdeer (*Charadrius vociferus*), lapwing (*Vanellus vanellus*), mallard (*Anas platyrhynchos*), piping plover (*Charadrius melodus; n*=6), snowy plover (*Charadrius alexandrinus;* Appendix 3). Combined data for redshank (*Tringa totanus*) and snipe (*Gallinago gallinago*) was provided by one study and a further six studies combined data for various duck species. All of these are ground-nesting species.

The majority of the 16 studies (81%) were a comparison of simultaneous sites or nests with and without predator exclusion. Two investigated hatching success before and after nest predators were excluded (Ivan and Murphy 2005; Anon. 2006) and one used a Before/After/Control/Impact design (Jackson 2001). The experimental and ecological characteristics of the studies included are illustrated in Figure 15.

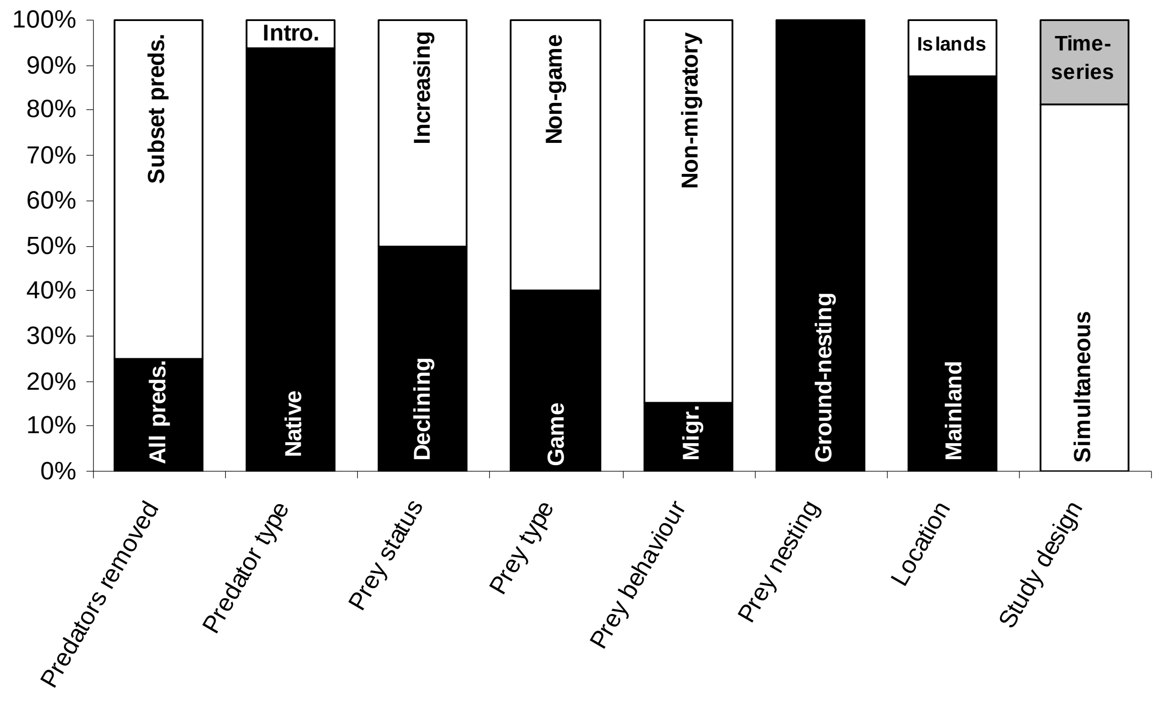

Figure 15. Ecological and experimental characteristics of predator exclusion studies included in the meta-analysis; proportions of total numbers are shown.

4.2.2. Meta-analysis

Predator exclusion

Evidence showed that overall nest predator exclusion (using either fences or nest-cages) significantly increased hatching success as indicated by a pooled effect size greater than zero and confidence intervals that do not overlap zero (DL SMD=1.578, z=4.74, p<0.001; Figure 16). There was significant heterogeneity between effect sizes (χ^2=57.12, *d.f.*=19, p<0.001). This heterogeneity was not explained by any of the variables investigated, although the relationship between effect size and study design (simultaneous sites/time-series) was close to significant (multivariate meta-regression: r= -5.540, SE=2.286, p=0.015), with the three largest effect sizes coming from time-series studies. The relationship was not close to significant once multiple testing was accounted for using Bonferroni's correction (α=0.005).

Sensitivity analysis using response ratios confirmed that the pooled effect size was positive and significant, although the effect size was smaller with less variation than when Hedge's d was used as the effect size estimator (Figure 16).

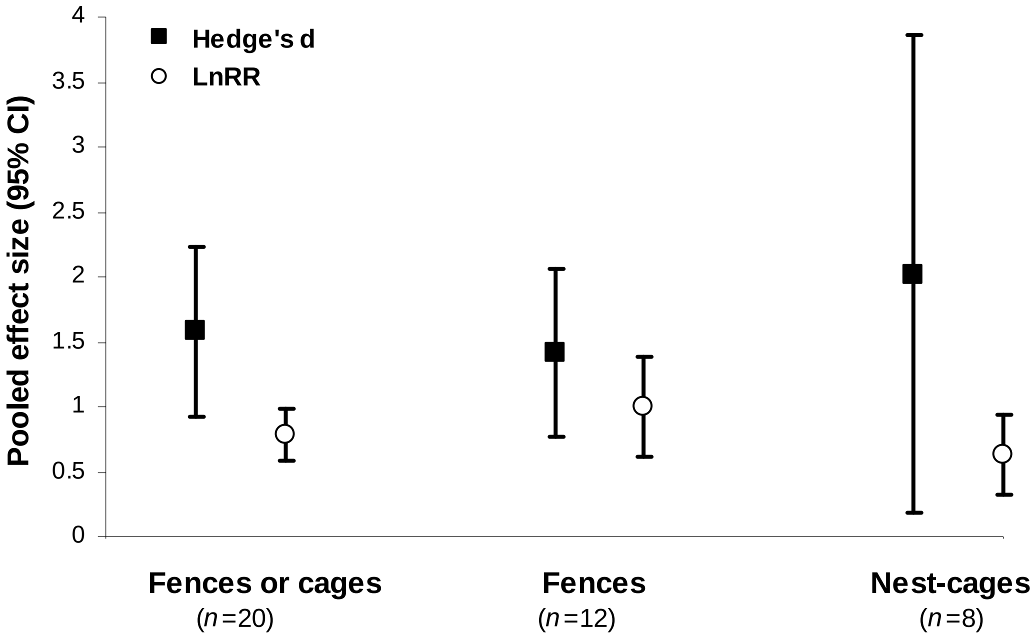

Figure 16. Pooled effect sizes and 95% confidence intervals for hatching success using Hedge's d and response ratios (RR) as the effect size estimators. Sample sizes (*n*) are also shown.

The funnel plot showed a pattern that suggested there may have been some publication bias as it indicated that it was easier to publish small studies when the results indicated a large positive effect of nest predator exclusion (Figure 17). This bias could have resulted in an overestimate of the effect size, however, the study with a large positive effect size had a low weight and so was unlikely to have had a significant effect on the overall result; studies with large weights were evenly distributed around the pooled effect size (Figure 17). The failsafe number indicated that

237 non-significant studies would be needed to overturn the significant results and so even with some publication bias, the results can be considered a reliable estimate of the true effect (Rosenberg et al. 2000).

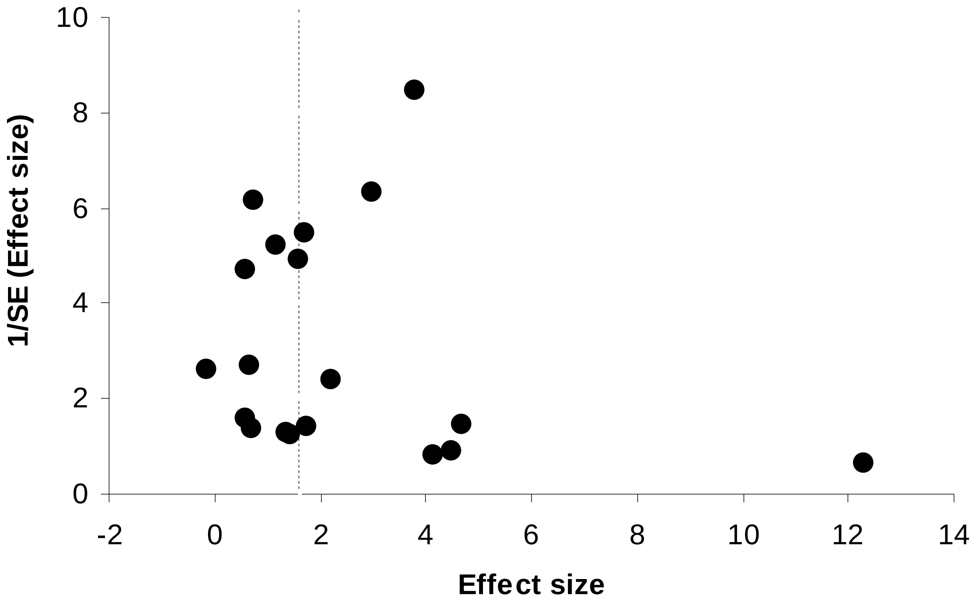

Figure 17. A funnel plot of the variation around the pooled effect size (dashed line = 1.578) for predator exclusion studies investigating hatching success; Hedge's d was used as the effect size estimator.

Exclusion fences

Nest predator exclusion using fences resulted in significant increases in hatching success (DL SMD=1.413, z=4.30, p<0.001; Figure 18). There was significant heterogeneity between effect sizes (χ^2=27.16, *d.f.*=11, p=0.004), but this was not explained by any of the variables investigated. The failsafe number indicated that 91 non-significant studies would be needed to overturn the significant results and so the estimate can be considered reliable.

Sensitivity analysis using response ratios rather than Hedge's d as the effect size estimator confirmed that the pooled effect size was positive and significant for exclusion fence studies, although effect sizes were smaller with less variation when using log response ratios (Figure 17).

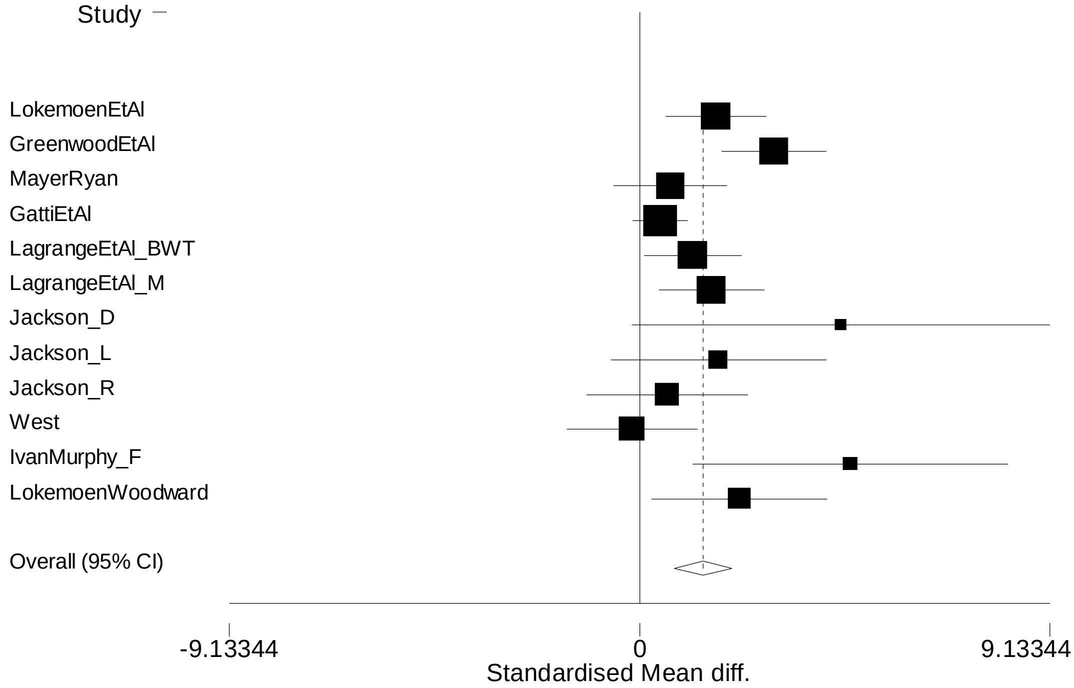

Figure 18. Forrest plot illustrating the variation in effect sizes (solid boxes) for hatching success studies where predators were excluded with fences; Hedge's d was used as the estimator. The solid vertical line represents the line of no effect (0); the dashed line and open diamond indicate the pooled effect. Box size is related to sample size and error bars are 95% confidence intervals. (Letters after author names indicate species; see Appendix 3).

Nest-cages

Meta-analysis of effect sizes from studies using nest-cages to exclude nest predators showed a significant increase in hatching success (DL SMD=2.023, z=2.16, p<0.031; Figure 19). However, the failsafe number was 26 which was less than 5n+10 (=50, where n is the number of cases analysed), meaning that the results cannot be considered a reliable estimate of the true effect (Rosenberg et al. 2000). There was significant heterogeneity between effect sizes (χ^2=26.47, *d.f.*=7, p<0.001), but this was not explained by any of the variables investigated.

Similar to results for exclusion fence studies, results from analysis of nest-cage studies using response ratios confirmed that the pooled effect size was positive and significant, although effect sizes were smaller with less variation than when Hedge's d was used as the effect size estimator (Figure 17).

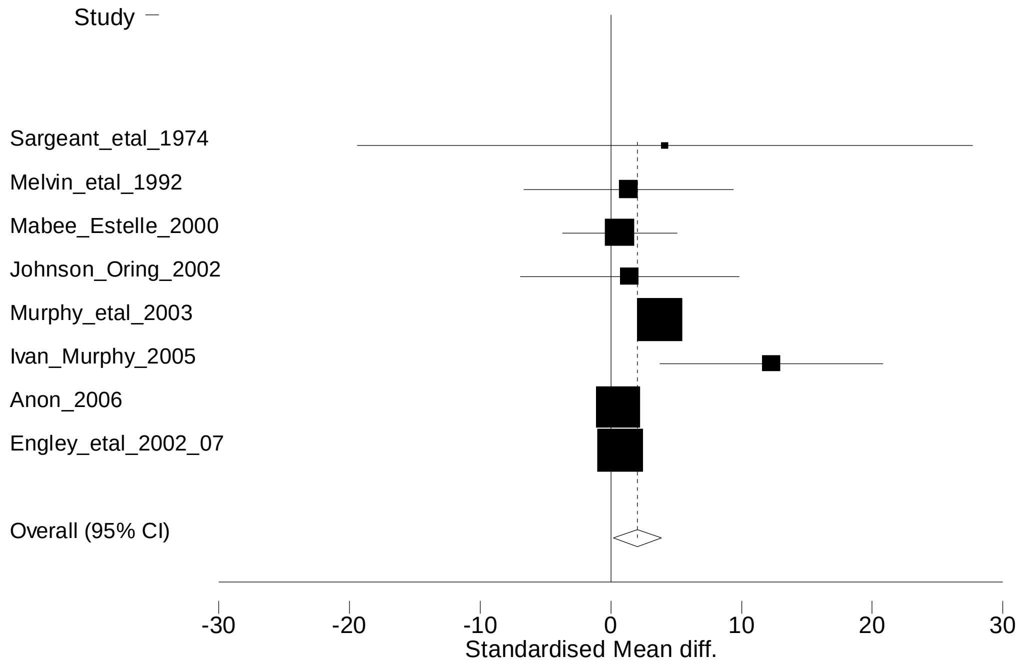

Figure 19. Forrest plot illustrating the variation in effect sizes (solid boxes) for hatching success studies where predators were excluded with nest-cages; Hedge's d was used the estimator. The solid vertical line represents the line of no effect (0); the dashed line and open diamond indicate the pooled effect. Box size is related to sample size and error bars are 95% confidence intervals.

The pooled effect size for hatching success with nest predator exclusion using either exclusion fences or nest-cages (DL SMD=1.578, 95% CI=0.925-2.231) was larger than that for predator removal (DL SMD=0.741, 95% CI=0.439-1.044), but the difference was not significant. The same was true for the pooled effect sizes for predator exclusion using just fences (DL SMD=1.413, 95% CI=0.769-2.057) or nest-cages (DL SMD=2.023, 95% CI=0.184-3.862).

A number of individual studies indicated that nest-cages can lead to increased levels of predation on incubating adults (Table 3; Nol and Brooks 1982; Johnson and Oring 2002; Murphy et al. 2003; Neuman et al. 2004; Isaksson et al. 2007).

Table 3. Evidence of predation on adult birds inside or near nest-cages.

Bird species	Evidence	Reference
Killdeer *(Charadrius vociferous)*	Mink *(Mustela vison)* killed an incubating adult inside 2 exclosures (*n*=12 nests).	Nol and Brooks 1982
Killdeer *(Charadrius vociferous)*	Long-tailed weasels *(Mustela frenata)* killed an incubating adult inside 4 exclosures (*n*=52 nests).	Johnson and Oring 2002
Piping plover (*Charadrius melodus)*	Higher predation (apparently by raptors) on incubating adult birds near protected nests (68 of 1355 nests) than near unprotected nests (0 of 420 nests).	Murphy et al. 2003
Snowy plover *(Charadrius alexandrinus)*	Less than half the nests were exclosed but 76% of 25 incubating adults that disappeared (presumed dead) were nesting in exclosures; adult mortality in exclosures was greater than expected by chance (χ^2=7.0, P<0.01).	Neuman et al. 2004
Lapwing (*Vanellus vanellus*)	No predation on adult birds in protected (*n*=37) or unprotected nests (*n*=153).	Isaksson et al. 2007
Redshank (*Tringa totanus*)	Higher predation on adult birds in protected nests (8 of 37 nests) than unprotected nests (1 of 31 nests; *p*=0.03, Fisher's exact test).	Isaksson et al. 2007

5. DISCUSSION

5.1 Evidence of effectiveness

This systematic review provides considerable evidence that predator removal has a significant positive impact on breeding bird population numbers, as well as increased hatching and fledging success as shown previously by Côté and Sutherland (1997). The pooled effect sizes for all three population parameters were moderate to large (Lipsey & Wilson, 2001). There was no relationship between effect size and prey population status, indicating that predator removal was an effective management strategy for declining (42% of cases) as well as increasing species. In contrast to the results of Côté and Sutherland (1997), overall the evidence suggested that predator removal did not result in increased post-breeding populations. There was significant heterogeneity in effect sizes for all four population parameters (discussed below).

Evidence suggested that excluding nest predators using either exclusion fences or nest-cages was an effective strategy for increasing the hatching success of bird populations. This was the case for both increasing and declining species indicating that it is an effective strategy for the conservation management of vulnerable bird populations. Nest-cages had a larger effect on hatching success than exclusion fences, although the difference was not significant. In fact, these two exclusion methods are not directly comparable as they have been used in different situations. Further studies comparing the two methods for the same species in similar habitats would be required to investigate this in more detail. There was significant heterogeneity between effect sizes for both exclusion fence and nest-cage studies (discussed below).

5.2 Reasons for variation in effectiveness

A significantly larger increase in breeding population was achieved by removing all predator species rather than just a subset. This has also been shown in ecological experiments (Trautman et al. 1974; Norrdahl & Korpimäki 2000). Introduced predators have been shown to have double the impact of native predators on prey populations (Salo et al. 2007), although this result was driven by the impact of introduced predators on the mammal community in Australia; in the current study we found that effect sizes did not differ between native and exotic predators. There are a number of other factors relating to predator ecology and behaviour that we did not investigate, but that may alter the effectiveness of predator removal studies. For example, we did not investigate predator taxa in this review; removing mammalian predators has been shown to be more effective than removing avian predators (Holt et al. 2008).

Ground-nesting species are often thought to be more vulnerable to predation than those nesting off the ground. Although this covariate explained some of the heterogeneity in effect sizes for fledging success, the difference in the effect of predator removal on ground-nesting and other species was not significant. Côté and Sutherland (1995), in their review of 110 studies, also found that there was no difference in the rates of nest predation of ground-nesting versus other bird species.

Evidence indicated that predator removal resulted in increased post-breeding populations on mainlands, but that there was no significant change in post-breeding populations on islands. This helps to explain the conflicting overall results from this and the previous review, as Côté and Sutherland (1997) who concluded that predator removal resulted in increased post-breeding populations, only included two cases from islands (Marcstrom et al. 1988; Robertson et al. 1994). In this review 38% of predator removal studies were from islands. There was no relationship between location and effect size for any of the other population parameters indicating that predator removal was effective at increasing hatching success, fledging success and breeding populations on both islands and mainlands. The study methodology, whether the prey was a game or migratory species or not did not explain any of the heterogeneity for any of the population parameters.

Effect sizes for hatching success, although heterogeneous for both predator removal and exclusion studies, were not significantly related to any of the covariates investigated. Small sample sizes may have been one of the reasons for this for exclusion fences (n=12 cases) and particularly for nest-cages (n=8).

5.3 Review limitations

The primary limitations of the review are down to the nature of the evidence-base. For example, with respect to study quality, a significant number of studies were only carried out for one year (particularly nest-cage studies), were poorly replicated and/or insufficiently reported. In addition, BACI designs, time-series and simultaneous site comparisons were combined. These different designs have their problems in terms of true effects. Effect sizes resulting from studies in which bird population parameters were measured before and after predator removal was initiated could be attributed to changes in the study site and climate over the two time periods. By measuring parameters over the same time period at different locations helps to avoid such problems but the sites selected could have varied in numerous ways such as habitat type or initial prey and/or predator density. Few studies reported using sites paired on these types of variables, or selected removal and control sites randomly to reduce bias. We did, however, explore heterogeneity due to study design and found no relationship with effect size.

Prey species investigated for predator removal or exclusion studies are not a random sample. Studies are more likely to be carried out on populations of species that are thought to be limited by predation than those that are not, or focus on cases from game or prey conservation studies as it is often unethical to remove predators. This may have resulted in inflated pooled effect sizes compared to a random set of prey species. In this review 78% of the predator removal studies investigated ground-nesting species, 42% of predator removal cases were declining species and 36% were game species. We disaggregated species within studies and analysed them as separate cases as the effect of predator removal is likely to vary for different species, this meant that not all cases were independent, which may have had some effect on the results. However, due to the substantial sample sizes and the fact that we investigated heterogeneity in effects between studies, it is thought unlikely to have had a significant effect on the overall results. We were unable to investigate the effect of predator control on separate species due to small sample sizes.

Exclosures tend to be used to protect ground-nesting species from nest predators, although they can be used for other species (e.g. Keo et al., 2009). During our literature search we found exclosure studies on non-ground-nesting species, but they could not be included in analyses as only one year of data was provided in each case (Post and Greenlaw, 1989; Yamaguchi et al., 2005; Debus, 2006). Data on fledging success were also extracted from exclosure studies, but sample sizes were too small to be included in analyses.

The majority of studies did not present data on the success of their predator reductions or eliminations, i.e. predator densities before and after removal and so this variable could not be included in our analyses. However, information that was provided indicated that 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).

As well as the limitations caused by the evidence available, there are a number of methodological limitations of the review. Steps were taken to minimise publication bias by searching the grey literature, but we are aware of literature that was not captured using the systematic searches. Also, no non-English publications were specifically searched for using foreign search terms, although any found during searches were translated and assessed for relevance in the same way as English publications. It is therefore possible that there are studies that were not identified despite our systematic efforts. Funnel plots indicated some potential for publication bias, with less favourable results potentially being unreported. This was the case for hatching success for removal and exclusion studies suggesting that the magnitude of the effects may have been overestimated. Despite this, failsafe numbers indicated that 589 and 237 non-significant studies respectively would be needed to overturn the significant results and so even with some publication bias, the results can be considered a reliable estimate of the true effect (Rosenberg et al. 2000).

6. REVIEWERS' CONCLUSIONS

6.1 Implications for management / policy / conservation

The available evidence suggested that predator control by either removing or excluding predators is an effective strategy for enhancing bird populations.

In contrast to the evidence reviewed by Côté & Sutherland (1997), our meta-analysis of available evidence suggested that predator removal fulfils the goals of conservation managers (to maintain or increase breeding population numbers) but does not always fulfil the goals of game managers (to enhance harvestable post-breeding populations). Results showed that predator removal resulted in an increase in early survival of birds, i.e. increased hatching and fledging success, but did not always result in an increase in post-breeding population. Predator removal did not lead to increased post-breeding populations on islands, but did result in increased numbers on mainlands. This means that on mainlands, predator removal is likely to be an effective strategy for gamekeepers (who want to enhance harvestable post-breeding populations).

Evidence suggested that predator removal can have long-lasting positive effects on prey populations, particularly following the eradication of predators from islands that cannot easily be re-colonized (Veitch 2002; Nordstrom 2003b). 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 that predator removal needs to be a long-term management strategy. Other options should therefore be explored and if resources are limited, as it is time-consuming and expensive, predator removal needs to be balanced against investing in habitat creation or improvement for example. Consideration must also be given to the effects of predator removal on the community as a whole. Removing a subset of predators for example can result in meso-predator release and/or 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). This may occur as exclusion fences are largely ineffective against avian predators and exclosures may not deter small predatory mammal species or snakes (Ivan and Murphy, 2005).

Evidence suggested that nest predator exclusion using either exclusion fences or nest-cages is an effective strategy for enhancing the hatching success of bird populations. However, data were not available to determine whether increased reproductive success resulted in increased breeding populations. A number of studies showed that nest-cages increased mortality rates of incubating adults. If this is the case and juvenile mortality is high in a particular species, even if hatching success is increased, nest-cages may have serious detrimental effect on population growth. In addition, unlike fencing, nest-cages cannot be put in place before breeding birds arrive at the breeding site and so cannot be left in place from year to year. This means that there is some disturbance of the breeding birds when the cages are placed over or around the nests (Nol and Brooks, 1982; Niehaus et al., 2004), which can take place before (Anon. 2006) or more usually sometime after clutch laying is completed. This can lead to abandonment of protected nests (Isaksson et al., 2007). Nest-cages should therefore be used with extreme caution for conservation purposes and avoided for small populations. In addition to being invasive, nest-cages tend to be more expensive per nest protected than fences and so may only be justified as a small scale emergency measure when nest predation is high and the prey species has a high conservation value (Jimenez et al., 2001).

6.2 Implications for research

Forty studies were omitted from our meta-analysis of predator removal studies (n=83) and nine from the meta-analysis of nest predator exclusion studies (n=16) as they lacked a control and/or spatial or temporal replicates and/or variation measures. Future studies should include the use of independent treatment and controls, replication and ensure effective reporting of data. There is currently a bias towards studies on ground-nesting species and a fairly high proportion of studies on game species (36%), mainly in temperate regions, and so future studies should concentrate on other groups of bird species in different areas of the world.

To have more confidence in the true effect of predator removal on post-breeding populations, more studies are required, particularly on islands. The same is true for nest predator exclusion studies using exclusion fences and especially using nest-cages as sample sizes are currently low. An increase in the number of nest predator exclusion studies may help to determine the factors responsible for the heterogeneity in effect sizes. Investigation into the difference in effect size for hatching success from time-series and simultaneous site studies is needed as there were indications that this may explain some of the heterogeneity. Additional studies are also required looking specifically at potential reasons for the heterogeneity in effect sizes for breeding populations following predator removal.

It is vital that further studies are carried out to determine whether nest-cages lead to increased mortality of incubating adults and whether the improved hatching success resulting from predator exclusion leads to increased breeding population size. Improving hatching success alone will not ensure improved conservation status of vulnerable prey species. Studies comparing the hatching success following the use of fences and nest-cages of the same species in similar habitats would also be beneficial to determine which method is the most effective.

7. ACKNOWLEDGEMENTS

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8. POTENTIAL CONFLICTS OF INTEREST AND SOURCES OF SUPPORT

No conflicts of interest declared.
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10. APPENDICIES

Appendix 1. Ecological and experimental characteristics and outcomes of the predator removal studies included in the meta-analysis; Hedge's d was used as the effect size estimator.

Authors	Predators removed	All / subset	Native/ Introduced	Prey species	Status (Inc, dec, stable)	Game/ Non-game	Migratory/ Non-migr.	Ground-nest/ Non-gr.-n.	Island/ mainland	Effect size - Hatching	Effect size - Fledging	Effect size - Post-breeding	Effect size - Breeding	Study Design (Before-After/ During-Post / Removal-Control-reversal)
Amar & Redpath 2002	Hooded Crow	A	N	Hen Harrier (*Circus cyaneus*)	St	N-G	N-M	GN	Isl	1.16				BA
Anderson & Devlin 1999	Gulls	S	N	Arctic Tern (*Sterna paradisaea*)	D	N-G	Mig	GN	Isl				0.18	BA
Anderson & Devlin 1999	Gulls	S	N	Common Tern (*Sterna hirundo*)	D	N-G	Mig	GN	Isl				2.36	BA
Anderson & Devlin 1999	Gulls	S	N	Roseate Tern (*Sterna dougallii*)	D	N-G	Mig	GN	Isl				2.30	BA
Armstrong et al. 2006	Black rat & brush-tailed possum	S	I	North Island Robin (*Petroica australis longipes*)	In	N-G	N-M	N-GN	M		1.47			DP
Baines et al. 2004	All carnivores	S	N	Capercaillie (*Tetrao urogallus*)	D	G	N-M	GN	M	1.69				RC
Balser et al. 1968	All carnivores	A	N	Blue-winged Teal (*Anas discors*), Mallard (*A. platyrhynchos*), Gadwall (*A. strepera*)	D	G	Mig	GN	M	1.10		0.48	0.03	RC-r
Beasom 1974	All mammals	S	N	Bobwhite Quail (*Colinus virginianus*)	D	G	N-M	GN	M	0.21	0.38	0.33		RC
Beasom 1974	All mammals	S	N	Wild Turkey (*Meleagris gallopavo*)	In	G	N-M	GN	M			0.70		RC
Blankinship 1966	Great-tailed Grackle	S	N	White-winged Dove (*Zenaida asiatica*)	St	N-G	N-M	N-GN	M	0.59		5.93	5.41	RC
Bolton et al. 2007	Red fox & Carrion Crow	S	N	Northern Lapwing (*Vanellus vanellus*)	D	N-G	N-M	GN	M	-0.10				RC
Butler 2003	All mammals	A	I	Blackbird (*Turdus merula*)	St	N-G	N-M	N-GN	M			0.19	0.27	RC
Butler 2003	All mammals	A	I	Chaffinch (*Fringilla coelebs*)	St	N-G	N-M	N-GN	M			0.57	-0.20	RC
Butler 2003	All mammals	A	I	Fantail (*Rhipidura fuliginosa*)	St	N-G	N-M	N-GN	M			0.78	-1.23	RC
Butler 2003	All mammals	A	I	Grey Warbler (*Gerygone igata*)	St	N-G	N-M	N-GN	M			0.13	-0.21	RC
Butler 2003	All mammals	A	I	New Zealand Bellbird (*Anthornis melanura*)	St	N-G	N-M	N-GN	M			3.42	0.81	RC
Butler 2003	All mammals	A	I	New Zealand Robin (*Petroica australis*)	St	N-G	N-M	N-GN	M		1.00	-0.80	-0.93	RC
Butler 2003	All mammals	A	I	New Zealand Tomtit (*Petroica macrocephala*)	St	N-G	N-M	N-GN	M			0.98	0.28	RC
Butler 2003	All mammals	A	I	Parakeet	D	N-G	N-M	GN	M			0.68	0.39	RC
Butler 2003	All mammals	A	I	Rifleman (*Acanthisitta chloris*)	St	N-G	N-M	GN	M			2.51	1.46	RC
Butler 2003	All mammals	A	I	Silvereye (*Zosterops lateralis*)	St	N-G	N-M	N-GN	M			0.21	-1.05	RC
Butler 2003	All mammals	A	I	Song Thrush (*Turdus philomelos*)	St	N-G	N-M	N-GN	M			1.00	-0.26	RC

Butler 2003	All mammals	A	I	Tui (*Prosthemadera novaeseelandiae*)	St	N-G	N-M	N-GN	M			1.27	0.23	RC
Byrd et al. 1997	Arctic fox	A	I	Black Oystercatcher (*Haematopus bachmani*)	In/st	N-G	N-M	GN	Isl				-1.69	RC
Byrd et al. 1997	Arctic fox	A	I	Pigeon Guillemot (*Cepphus columba*)	St	N-G	N-M	GN	Isl				-2.62	RC
Chesness et al. 1968	All carnivores	A	N	Common Pheasant (*Phasianus colchicus*)	St	G	N-M	GN	M	1.87		1.61	-0.19	RC
Chodachek 2003	Med.-size mammals	S	N	American Wigeon (*Anas americana*)	In/st	G	Mig	GN	M				-0.02	RC
Chodachek 2003	Med.-size mammals	S	N	Blue-winged Teal (*Anas discors*)	In	G	Mig	GN	M				0.08	RC
Chodachek 2003	Med.-size mammals	S	N	Gadwall (*Anas strepera*)	In	G	Mig	GN	M				0.09	RC
Chodachek 2003	Med.-size mammals	S	N	Green-winged Teal (*Anas carolinensis*)	In	G	Mig	GN	M				0.17	RC
Chodachek 2003	Med.-size mammals	S	N	Mallard (*Anas plathyrhynchos*)	In	G	N-M	GN	M				0.13	RC
Chodachek 2003	Med.-size mammals	S	N	Northern Pintail (*Anas acuta*)	D	G	Mig	GN	M				0.22	RC
Chodachek 2003	Med.-size mammals	S	N	Northern Shoveler (*Anas clypeata*)	In	G	Mig	GN	M				0.12	RC
Chodachek 2003	Med.-size mammals	S	N	Upland nesting ducks	In	G	Mig	GN	M	14.25				RC
Clark et al. 1995	American Crow	S	N	Upland ducks	In	G	Mig	GN	M	0.19				RC
Clark et al. 1995	American Crow	S	N	Various ducks	St	G	Mig	GN	M				0.00	RC
Crissey & Darrow 1949	All carnivores	A	N	Ruffed Grouse (*Bonasa umbellus*)	In/st	G	N-M	GN	M	-0.34		-2.24	-0.96	RC
Cruz & Cruz 1996; Coulter et al. 1981; Tompkis et al. 1985	All mammals	A	I	Galapagos Dark-rumped Petrel (*Pterodroma phaeopygia phaeopygia*)	D	N-G	Mig	GN	Isl		0.71			BA
Darrow 1947	All carnivores	A	N	Ruffed Grouse (*Bonasa umbellus*)	In/st	G	N-M	GN	M			-0.12	-0.44	RC-r
De Groot et al. 1999	Brown-headed Cowbird	S	N	Song Sparrow (*Melospiza melodia*)	St	N-G	N-M	GN	M	2.08				RC/ BA
Duebbert & Kantrund 1974	Med.-size mammals	S	N	Various ducks	In/st	G	N-M	Mix	M	1.80				RC
Duebbert & Kantrund 1974	Med.-size mammals	S	N	Various ducks	In/st	G	N-M	GN	M				1.64	RC
Duebbert & Lokemoen 1980	All mammals	A	N	American Wigeon (*Anas americana*)	In	G	Mig	GN	M	0.04			0.52	DP
Duebbert & Lokemoen 1980	All mammals	A	N	Blue-winged Teal (*Anas discors*)	In	G	Mig	GN	M	0.65			1.72	DP
Duebbert & Lokemoen 1980	All mammals	A	N	Gadwall (*Anas strepera*)	In	G	Mig	GN	M	0.44			0.75	DP
Duebbert & Lokemoen 1980	All mammals	A	N	Green-winged Teal (*Anus crecca*)	In	G	Mig	GN	M	0.00			1.98	DP
Duebbert & Lokemoen 1980	All mammals	A	N	Mallard (*Anas platyrhynchos*)	In	G	N-M	GN	M	1.08			0.61	DP
Duebbert & Lokemoen 1980	All mammals	A	N	Northern Pintail (*Anas acuta*)	In	G	Mig	GN	M	-0.56			0.81	DP
Duebbert & Lokemoen 1980	All mammals	A	N	Northern Shoveler (*Anus clypeata*)	In	G	Mig	GN	M	0.52			1.19	DP
Duebbert & Lokemoen 1980	All mammals	A	N	Various ducks	In	G	Mig	GN	M	1.50			1.09	DP
Edminster 1939	Mammals	S	N	Ruffed Grouse (*Bonasa umbellus*)	In/st	G	N-M	GN	M					RC-r
Elliott & Suggate 2007	Rats	A	I	Mohua (*Mohoua ochrocephala*)	D	N-G	N-M	GN	M				2.77	BA

Finney et al. 2003	Gulls	A	N	Atlantic Puffin (*Fratercula arctica*)	In	N-G	Mig	GN	Isl			-0.35	RC
Fletcher et al. 2005; Fletcher 2007	All mammals	A	N	Eurasian Curlew (*Numensis arquata*)	D	N-G	Mig	GN	M			1.19	RC-r
Fletcher et al. 2005; Fletcher 2007	All mammals	A	N	Eurasian Golden Plover (*Pluvialis apricaria*)	D	N-G	N-M	GN	M			0.65	RC-r
Fletcher et al. 2005; Fletcher 2007	All mammals	A	N	Northern Lapwing (*Vanellus vanellus*)	D	N-G	N-M	GN	M			1.49	RC-r
Fletcher et al. 2005; Fletcher 2007	All mammals	A	N	Red Grouse (*Lagopus lagopus scoticus*)	In/st	G	N-M	GN	M			1.19	RC-r
Frank 1970	All carnivores	A	N	Grey Partridge (*Perdix perdix*)	In/st	G	N-M	GN	M		1.08		RC
Frey et al. 2003	All mammals	S	N	Common Pheasant (*Phasianus colchicus*)	D	G	N-M	GN	M		0.34		RC
Frey et al. 2003	All mammals	S	N	Ring-necked Pheasant (*Phasianus colchicus*)	D	G	N-M	GN	M			0.01	RC-r
Garrettson & Rohwer 2001	Mammals	S	N	Upland nesting ducks	In	G	Mig	GN	M	1.77		0.44	RC
Garrettson et al. 1996	Mammals	S	N	American Coot (*Fulica Americana*)	In	N-G	N-M	GN	M	1.53			RC
Garrettson et al. 1996	Mammals	S	N	Diving ducks (*Aythya americana, Aythya valisineria, Oxyura jamaicensis*)	St	G	Mig	GN	M	1.88			RC
Garrettson et al. 1996	Mammals	S	N	Yellow-headed Blackbird (*Xanthocephalus xanthocephalus*)	In	N-G	Mig	N-GN	M	0.02			RC
Giradet et al. 2001	Domestic cat	S	I	Blackbird (*Turdus merula*)	St	N-G	N-M	N-GN	Isl		0.87		BA
Giradet et al. 2001	Domestic cat	S	I	Fantail (*Rhipidura fuliginosa*)	St	N-G	N-M	N-GN	Isl		-0.52		BA
Giradet et al. 2001	Domestic cat	S	I	Grey Warbler (*Gerygone igata*)	St	N-G	N-M	N-GN	Isl		0.03		BA
Giradet et al. 2001	Domestic cat	S	I	Kākā (*Nestor meridionalis*)	D	N-G	N-M	N-GN	Isl		0.44		BA
Giradet et al. 2001	Domestic cat	S	I	New Zealand Bellbird (*Anthornis melanura*)	St	N-G	N-M	N-GN	Isl		0.17		BA
Giradet et al. 2001	Domestic cat	S	I	New Zealand Pigeon (*Hemiphaga novaeseelandiae*)	D	N-G	N-M	N-GN	Isl		0.04		BA
Giradet et al. 2001	Domestic cat	S	I	New Zealand Robin (*Petroica australis*)	St	N-G	N-M	N-GN	Isl		0.36		BA
Giradet et al. 2001	Domestic cat	S	I	New Zealand Tomtit (*Petroica macrocephala*)	St	N-G	N-M	N-GN	Isl		-0.73		BA
Giradet et al. 2001	Domestic cat	S	I	Red-crowned Parakeet (*Cyanoramphus novaezelandiae*), Yellow-crowned Parakeet (*Cyanoramphus auriceps*)	D	N-G	N-M	GN	Isl		-6.09		BA
Giradet et al. 2001	Domestic cat	S	I	Rifleman (*Acanthisitta chloris*)	St	N-G	N-M	GN	Isl		0.04		BA
Giradet et al. 2001	Domestic cat	S	I	Silvereye (*Zosterops lateralis*)	St	N-G	N-M	N-GN	Isl		0.45		BA
Giradet et al. 2001	Domestic cat	S	I	Stitchbird (*Notiomystis cincta*)	St	N-G	N-M	N-GN	Isl		-0.51		BA
Giradet et al. 2001	Domestic cat	S	I	Tui (*Prosthemadera novaeseelandiae*)	St	N-G	N-M	N-GN	Isl		0.36		BA
Giradet et al. 2001	Domestic cat	S	I	Whitehead (*Mohoua albicilla*)	St	N-G	N-M	N-GN	Isl		0.36		BA
Grant et al. 1997	Mammals	S	I	Chatham Island Pigeon (*Hemiphaga novaeseelandiae chathamensis*)	D	N-G	N-M	N-GN	Isl			1.10	BA
Greenwood 1986	Striped skunk	S	N	Various ducks	In/st	G	N-M	Mix	M	1.09			RC

Guthery & Beasom 1977	All mammals	A	N	Bobwhite Quail (*Colinus virginianus*)	D	G	N-M	GN	M			-0.15	-0.41	RC
Guthery & Beasom 1977	All mammals	A	N	Scaled Quail (*Callipepla squamata*)	D	G	N-M	GN	M			-0.09	-0.12	RC
Hario 1994	Gulls	S	N	Lesser Black-backed Gull (*Larus fuscus*)	D	N-G	Mig	GN	Isl		0.95		-0.60	BA
Harper 2007	Black rat	A	I	Sooty Shearwater (*Puffinus griseus*)	D	N-G	Mig	GN	Isl	-0.36				RC
Harris & Wanless 1997	Gulls	A	N	Oystercatcher (*Haematopus ostralegus*)	St	N-G	N-M	GN	Isl				2.38	BA
Hill 1988	Black-headed Gulls	S	N	Avocet (*Recurvirostra avocetta*)	D	N-G	N-M	GN	M		0.40		1.12	BA
Imber et al. 2000	Brown rat	A	I	Grey-faced Petrel (*Pterodroma macroptera gouldi*)	D	N-G	Mig	GN	Isl		2.50			BA
Imber et al. 2003	Domestic cat	S	I	Cook's Petrel (*Pterodroma cookii*)	D	N-G	Mig	GN	Isl		-1.20			BA
Innes et al. 1999	All mammals	A	I	North Island Kokako (*Callaeus cinereus wilsoni*)	D	N-G	N-M	N-GN	M		1.14		-1.07	RC-r
Innes et al. 2004	Mammals	S	I	New Zealand Pigeon (*Hemiphaga novaeseelandiae*)	D	N-G	N-M	N-GN	M				2.32	RC
James & Clout 1996	Black rat	S	I	New Zealand Pigeon (*Hemiphaga novaeseelandiae*)	D	N-G	N-M	N-GN	M	4.75	3.96			RC
Jouventin et al. 2003	Black rat	A	I	Subantarctic White-chinned Petrel (*Procellaria aequinoctialis*)	D	N-G	Mig	GN	Isl		-0.03		-0.40	RC/ BA
Kauhala 2004	Med.-size mammals	S	N	Dabbling ducks	In/st	G	Mig	Mix	M	0.20			-0.73	RC
Kauhala 2004	Med.-size mammals	S	N	Diving ducks	In/st	G	Mig	Mix	M	0.46			0.09	RC
Kauhala et al. 2000	Small-med. mammals	S	N	Black Grouse (*Tetrao tetrix*)	D	G	N-M	GN	M			1.39		RC
Keedwell et al. 2002; Pierce 1986	All carnivores	A	I	Black Stilt (*Himantopus novaezelandiae*)	D	N-G	N-M	GN	M		0.66			RC
Kelly et al. 2005	Stoat	S	I	New Zealand Bellbird (*Anthornis melanura*)	St	N-G	N-M	N-GN	M				2.03	RC
Lawrence & Silvy 1995	Med.-size mammals	S	N	Attwater's Prairie-Chicken (*Tympanuchus cupido attwateri*)	D	G	N-M	GN	M	1.36				BA
Le Nevé 2005	Rats & gulls	A	N	Common Tern (*Sterna hirundo*)	D	N-G	Mig	GN	Isl				0.51	BA
Le Nevé 2005	Rats & gulls	A	N	Sandwich Tern (*Sterna sandvicensis*)	D	N-G	Mig	GN	Isl				1.16	BA
Little & Crowe 2004	Small mammals	S	N	Grey-winged Francolin (*Scleroptila africanus*)	St	G	N-M	GN	M			-0.39		RC-r
Littlefield 2003	Mammals & Corvids	S	N	Greater Sandhill Crane (*Grus canadensis tabida*)	In	N-G	Mig	GN	M	0.91	1.08		-0.53	BA
MacDonald 1966	Coyote & bobcat	S	N	Wild Turkey (*Meleagris gallopavo*)	D	G	N-M	GN	M				-0.09	RC
Marcström et al. 1988	Fox & marten	S	N	Black Grouse (*Tetrao tetrix*)	In	G	N-M	GN	Isl				0.95	RC-r
Marcström et al. 1988	Fox & marten	S	N	Capercaillie (*Tetrao urogallus*)	In	G	N-M	GN	Isl				0.25	RC-r
Marcström et al. 1988	Fox & marten	S	N	Tetronids-Capercaillie (*Tetrao urogallus*), Black Grouse (*Tetrao tetrix*), Hazel Grouse (*bonasa banasia*), Willow Grouse (*Lagopus lagopus*)	In	G	N-M	GN	Isl			0.20		RC-r
Meckstroth & Miles 2005	Mammals	S	N	Black-necked Stilt (*Himantopus mexicanus*), American Avocet (*Recurvirostra americana*)	St	N-G	N-M	GN	M	-1.02				RC

Nordström et al. 2002	American mink	A	I	Common Eider (*Somateria mollissima*)	St	G	N-M	GN	Isl				0.32	RC
Nordström et al. 2002	American mink	A	I	Common Merganser (*Mergus merganser*)	D	G	Mig	N-GN	Isl				0.14	RC
Nordström et al. 2002	American mink	A	I	Common Shelduck (*Tadorna tadorna*)	In	G	Mig	GN	Isl				2.10	RC
Nordström et al. 2002	American mink	A	I	Greylag Goose (*Anser anser*)	In	G	Mig	GN	Isl				1.26	RC
Nordström et al. 2002	American mink	A	I	Mallard (*Anas plathyrhynchos*)	D	G	Mig	GN	Isl				1.80	RC
Nordström et al. 2002	American mink	A	I	Mute Swan (*Cygnus olor*)	In	G	N-M	GN	Isl				-0.59	RC
Nordström et al. 2002	American mink	A	I	Tufted Duck (*Aythya fuligula*)	D	G	N-M	GN	Isl				1.33	RC
Nordström et al. 2002	American mink	A	I	Velvet Scooter (*Melanitta fusca*)	In	G	Mig	GN	Isl				1.05	RC
Nordström et al. 2003	American mink	A	I	Arctic Skua (*Stercorarius parasiticus*)	St	N-G	Mig	GN	Isl				0.92	RC
Nordström et al. 2003	American mink	A	I	Arctic Tern (*Sterna paradisaea*)	In	N-G	Mig	GN	Isl				1.29	RC
Nordström et al. 2003	American mink	A	I	Common Gull (*Larus canus*)	In	N-G	Mig	GN	Isl				0.82	RC
Nordström et al. 2003	American mink	A	I	Common Redshank (*Tringa totanus*)	D	N-G	Mig	GN	Isl				1.67	RC
Nordström et al. 2003	American mink	A	I	Common Ringed Plover (*Charadrius hiaticula*)	D	N-G	Mig	GN	Isl				2.09	RC
Nordström et al. 2003	American mink	A	I	Great Black-headed Gull (*Larus marinus*)	In/st	N-G	N-M	GN	Isl				0.33	RC
Nordström et al. 2003	American mink	A	I	Meadow Pipit (*Anthus pratensis*)	St	N-G	Mig	GN	Isl				0.38	RC
Nordström et al. 2003	American mink	A	I	Oystercatcher (*Haematopus ostralegus*)	In	N-G	Mig	GN	Isl				2.15	RC
Nordström et al. 2003	American mink	A	I	Rock Pipit (*Anthus petrosus*)	D	N-G	Mig	GN	Isl				0.29	RC
Nordström et al. 2003	American mink	A	I	Ruddy Turnstone (*Arenaria interpres*)	St	N-G	N-M	GN	Isl				2.11	RC
Nordström et al. 2003	American mink	A	I	Wheatear (*Oenanthe oenanthe*)	D	N-G	Mig	N-GN	Isl				0.72	RC
Nordström et al. 2003	American mink	A	I	White Wagtail (*Motacilla alba*)	D	N-G	Mig	GN	Isl				0.05	RC
Nordström et al. 2004	American mink	A	I	Arctic Tern (*Sterna paradisaea*)	In	N-G	Mig	GN	Isl		0.35			RC
Norrdahl & Korpimäki 2000	Mammals & raptors	S	N	Common Pheasant (*Phasianus colchicus*), Grey Partridge (*Perdix perdix*)	St	G	N-M	GN	M			-0.23	0.17	RC
Norrdahl & Korpimäki 2000	Mammals & raptors	S	N	Small ground-nesting birds	D	N-G	Mig	GN	M			0.33	0.08	RC
O'Donnell et al. 1996; Dilks 1999	Stoat	S	I	Mohua (*Mohoua ochrocephala*)	D	N-G	N-M	N-GN	M		0.93		-0.22	RC
Parker 1984	Corvids	S	N	Willow Ptarmigan (*Lagopus lagopus lagopus*)	St	G	N-M	GN	Isl	1.12			0.89	RC
Parr 1993	Crows & gulls	S	N	Eurasian Curlew (*Numenius arquata*)	St	N-G	Mig	GN	M	0.61			-0.30	BA
Parr 1993	Crows & gulls	S	N	Eurasian Golden Plover (*Pluvialis apricaria*)	D	N-G	N-M	GN	M	-1.18			-2.37	BA
Parr 1993	Crows & gulls	S	N	Northern Lapwing (*Vanellus vanellus*)	St	N-G	N-M	GN	M	0.60			-1.37	BA
Parr 1993	Crows & gulls	S	N	Oystercatcher (*Haematopus ostralegus*)	St	N-G	N-M	GN	M	0.92			0.37	BA

Parr 1993	Crows & gulls	S	N	Redshank (*Tringa totanus*)	St	N-G	Mig	GN	M	0.92			1.04	BA
Parr 1993	Crows & gulls	S	N	Snipe (*Gallinago gallinago*)	St	N-G	N-M	GN	M	0.18			1.70	BA
Pearse & Ratti 2004	Mammals	S	N	Mallard (*Anas plathyrhynchos*)	In	G	N-M	GN	M	0.88				RC
Potts 1980; Tapper et al. 1982	All carnivores	A	N	Grey Partridge (*Pedix perdix*)	D	G	N-M	GN	M				2.38	DP
Powlesland et al. 1999	Brushtail possum	S	I	North Island Robin (*Petroica australis longipes*)	St	N-G	N-M	N-GN	M				4.00	RC
Priddel & Carlile 1998	Pied Currawongs & Raven	A	N	Gould's Petrel (*Pterodroma leucoptera*)	D	N-G	Mig	GN	Isl		1.31		1.72	BA
Ratcliffe et al. 2005	American mink	S	I	Arctic Tern (*Sterna paradisaea*)	D	N-G	Mig	GN	Isl		0.25		-1.76	BA
Ratcliffe et al. 2005	American mink	S	I	Little Tern (*Sternula albifrons*)	D	N-G	Mig	GN	Isl		-0.38		-0.45	BA
Redpath 1991	Hen Harrier	S	N	Red Grouse (*Lagopus lagopus scoticus*)	D	G	N-M	GN	M		0.76			RC
Regehr et al. 2007	Rats	A	I	Anciet Murrelet (*Synthliboramphus antiquus*)	D	N-G	N-M	GN	Isl				-0.52	BA
Robertson et al. 1994; Robertson & Saul 2004; 2005; 2006; 2008	Rats	S	I	Kakerori (*Pomarea dimidiata*)	D	N-G	N-M	N-GN	Isl	1.42	2.11	1.32	1.13	RC/ BA
Sargeant et al. 1995	All mammals	A	N	Various ducks	In/st	G	Mig	GN	M	0.36				RC
Scottish Natural Heritage 2004	American mink	S	I	Northern Lapwing (*Vanellus vanellus*)	D	N-G	N-M	GN	Isl			3.58	1.52	RC
Seto & Conant 1996	Black rat	A	I	Bonin Petrel (*Pterodroma hypoleuca*)	D	N-G	N-M	GN	Isl	1.19	1.07			RC
Slagsvold 1980	Hooded Crow	S	N	Fieldfare (*Turdus pilaris*)	St	N-G	N-M	N-GN	M				3.20	BA/ RC
Slater 2003	Coyote	S	N	Sage-Grouse (*Centrocercus urophasianus*)	D	G	N-M	GN	M	-0.16	-0.08			RC
Street 1987	Mammals & Corvids	S	N	Canada Goose (*Branta canadensis*), Greylag Goose (*Anser anser*), Mallard (*Anas platyrhynchos*), Tufted Duck (*Aythya fuligula*)	In	N-G	N-M	GN	M	0.83				BA
Summers et al. 2004	Red fox & Carrion Crow	S	N	Black Grouse (*Tetrao tetrix*)	D	G	N-M	GN	M		1.75			BA
Summers et al. 2004	Red fox & Carrion Crow	S	N	Capercaillie (*Tetrao urogallus*)	D	G	N-M	GN	M		1.66			BA
Swann 2006; 2007	Brown rat	S	I	Black Guillemot (*Cepphus grylle*)	D	N-G	Mig	GN	Isl				0.47	BA
Swann 2006; 2007	Brown rat	S	I	Black-legged Kittiwake (*Rissa tridactyla*)	In	N-G	Mig	GN	Isl		-0.83		-1.98	BA
Swann 2006; 2007	Brown rat	S	I	Common Guillemot (*Uria aalge*)	D	N-G	Mig	GN	Isl				-0.48	BA
Swann 2006; 2007	Brown rat	S	I	Common Tern (*Sterna hirundo*)	D	N-G	Mig	GN	Isl				0.03	BA
Swann 2006; 2007	Brown rat	S	I	European Shag (*Phalacrocorax aristotelis*)	D	N-G	N-M	GN	Isl		0.90		-1.46	BA
Swann 2006; 2007	Brown rat	S	I	Great Black-backed Gull (*Larus marinus*)	D	N-G	N-M	GN	Isl		-0.17		-1.90	BA
Swann 2006; 2007	Brown rat	S	I	Great Skua (*Stercorarius skua*)	In	N-G	Mig	GN	Isl				1.83	BA
Swann 2006; 2007	Brown rat	S	I	Herring Gull (*Larus argentatus*)	D	N-G	N-M	GN	Isl		1.56		-1.53	BA
Swann 2006; 2007	Brown rat	S	I	Lesser Black-backed Gull (*Larus fuscus*)	D	N-G	Mig	GN	Isl				-1.37	BA

Swann 2006; 2007	Brown rat	S	I	Common Gull (*Larus canus brachyrhynchus*)	D	N-G	Mig	GN	Isl				0.10	BA
Swann 2006; 2007	Brown rat	S	I	Northern Fulmar (*Fulmaris glacialis*)	D	N-G	N-M	GN	Isl		-0.32		-3.14	BA
Swann 2006; 2007	Brown rat	S	I	Razorbill (*Alca torda*)	D	N-G	Mig	GN	Isl				0.82	BA
Tapper et al. 1996	Mammals & Corvids	S	N	Grey Partridge (*Perdix perdix*)	D	G	N-M	GN	M	6.83		1.82	-0.04	RC-r
Thibault 1995	Black rat	A	I	Cory's Shearwater (*Calonectris diomedea*)	St	N-G	Mig	GN	Isl		1.65			BA
Trautman et al. 1973; 1974	Med.-size mammals	S	N	Common Pheasant (*Phasianus colchicus*)	St	G	N-M	GN	M	-0.23		0.75	0.47	RC
Trautman et al. 1973; 1974	Red fox	S	N	Common Pheasant (*Phasianus colchicus*)	St	G	N-M	GN	M			0.96	0.48	RC
VanderWerf & Smith 2002	Rats	S	I	O'ahu 'Elepaio or Monarch Flycatcher (*Chasiempis sandwichensis*)	D	N-G	N-M	N-GN	Isl		1.68			RC-r/BA
Veitch 2002	Pacific rat	A	I	Pukeko or Purple Swamp Hen (*Porphyrio melanotus*)	In/st	N-G	N-M	GN	Isl				1.05	BA
Veitch 2002	Pacific rat	A	I	Saddleback (*Philesturnus carunculatus*)	In	N-G	N-M	N-GN	Isl				2.70	BA
Wanless & Kinnear 1988	Gulls	A	N	Arctic Tern (*Sterna paradisaea*)	In	N-G	Mig	GN	Isl				0.50	BA
Wanless & Kinnear 1988	Gulls	A	N	Common Eider (*Somateria mollissima*)	In	G	N-M	GN	Isl				1.46	BA
Wanless & Kinnear 1988	Gulls	A	N	Common Shelduck (*Tadorna tadorna*)	In	G	N-M	GN	Isl				1.03	BA
Wanless & Kinnear 1988	Gulls	A	N	Common Tern (*Sterna hirundo*)	St	N-G	Mig	GN	Isl				0.65	BA
Whitworth et al. 2005	Black rat	A	I	Xantus's Murrelet (*Synthliboramphus hypoleucus*)	D	N-G	N-M	GN	Isl	0.56				BA
Wills et al. 2003	All carnivores	A	I	New Zealand Dotteral (*Charadrius obscurus aquilonius*)	D	N-G	N-M	GN	Isl	1.39			1.36	RC
Wilson et al. 1998; Butler 2003; Moorhouse et al. 2003; Powlesland et al. 2003	Brushtail possum	S	I	Kākā (*Nestor meridionalis*)	D	N-G	N-M	N-GN	M	1.67	1.83			BA

Appendix 2.

2.1 Studies included in predator removal meta-analysis

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Appendix 3. Ecological and experimental characteristics and outcomes of the predator exclusion studies on hatching success included in the meta-analysis; Hedge's d was used as the effect size estimator.

Authors	Intervention (Fence / Cage)	Predators removed	All / Subset	Native/ Introduced	Prey species	Status (Inc / Dec / stable)	Game/ Non-game	Migratory/ Non-migr.	Island/ Mainland	Effect size	Study Design (Before-after / Removal-control)
Anon. 2006	C	Mammals, birds & crabs	A	N	Piping Plover (*Charadrius melodus*)	In	N-G	N-M	Isl	0.58	BA
Engley & Schmelzeisen 2002; Schmelzeisen & Engley 2003; Engley et al. 2004; Engley & Prescott 2005; Schmelzeisen et al. 2005; Rezansoff et al. 2006; van Huystee et al. 2007	C	Carnivores	A	N	Piping Plover (*Charadrius melodus*)	D	N-G	N-M	M	0.74	RC
Gatti et al. 1992	F	Med.-size mammals	S	N	Dabbling ducks	St	G	N-M	M	0.46	RC
Greenwood et al. 1990	F	Med.-size mammals	S	N	Upland nesting ducks	St	G	N-M	M	2.99	RC
Ivan & Murphy 2005	F	Med.-size mammals	S	N	Piping Plover (*Charadrius melodus*)	D	N-G	N-M	M	4.69	BA
Ivan & Murphy 2005	C (& F)	Med.-size mammals	S	N	Piping Plover (*Charadrius melodus*)	D	N-G	N-M	M	12.29	BA
Jackson 2001	F	Hedgehogs	A	I	Dunlin (*Calidris alpina*)	D	N-G	Mig	Isl	4.48	BACI
Jackson 2001	F	Hedgehogs	A	I	Northern Lapwing (*Vanellus vanellus*)	D	N-G	N-M	Isl	1.76	BACI
Jackson 2001	F	Hedgehogs	A	I	Redshank (*Tringa totanus*) & Snipe (*Gallinago gallinago*)	D	N-G	Mig; N-M	Isl	0.61	BACI
Johnson & Oring 2002	C	Med. Size mammals & birds	S	N	Killdeer (*Charadrius vociferus*)	St	N-G	N-M	M	1.44	RC
Lagrange et al. 1995	F	Med.-size mammals	S	N	Blue-winged Teal (*Anas discors*)	In	G	Mig	M	1.18	RC
Lagrange et al. 1995	F	Med.-size mammals	S	N	Mallard (*Anas platyrhynchos*)	In	G	N-M	M	1.60	RC
Lokemoen et al. 1982	F	Mammals	S	N	Various ducks	St	G	N-M	M	1.70	RC
Lokemoen & Woodward 1993	F	Mammals	S	N	Various ducks	In	G	N-M	M	2.22	RC
Mabeé & Estelle 2000	C	Med.-large size carnivores	S	N	Snowy Plover (Charadrius alexandrinus)	D	N-G	N-M	M	0.69	RC
Mayer & Ryan 1991	F	Mammals	S	N	Piping Plover (*Charadrius melodus*)	D	N-G	N-M	M	0.69	RC
Melvin et al. 1992	C	Mammals	S	N	Piping Plover (*Charadrius melodus*)	D	N-G	N-M	M	1.38	RC
Murphy et al. 2003	C	Mammals & birds	A	N	Piping Plover (*Charadrius melodus*)	D	N-G	N-M	M	3.79	RC
Sargeant et al. 1974	C	Mammals	S	N	Various ducks	In	G	N-M	M	4.15	RC
West 2002	F	Mammals	S	N	Cinnamon Teal (*Anas cyanoptera*), Gadwall (*Anas strepera*), Redhead (*Aythya americana*)	St	G	N-M	M	-0.16	RC

Appendix 4. Ecological and experimental characteristics and outcomes of predator exclusion studies that were not included in the meta-analysis as they provided quantitative data without variance measures or outcome measures other than hatching success.

Authors	Intervention (Cage / Fence / Anti-pred. nestbox)	Predators removed	Prey species	Island/ Mainland	Study Design	No. years removed	Output measure (Hatching success % / Daily nest survival rate)	Treatment	Control
Debus 2006	Cage	Pied Currawong	Yellow Robin (*Eopsaltria australis*)	M	RC	1	Hatching	83.30	37.50
Estelle et al. 1996	Cage	Avian & arctic fox	Pectoral Sandpiper (*Calidris melanotos*)	M	RC	1	Hatching	76.92	2.56
Gulickx and Kemp 2007	Cage	Red fox & corvids	Little Ringed Plover (Charadrius dubius)	M	BA	10	Fledging	0.69	0.62
Isaksson et al. 2007	Cage	Carnivores	Northern Lapwing (*Vanellus vanellus*)	M	RC	2	Daily surv.	0.99	0.97
Isaksson et al. 2007	Cage	Carnivores	Redshank (*Tringa totanus*)	M	RC	1	Daily surv.	1.00	0.97
Kruse et al. 2001	Cage	Carnivores	Piping Plover (*Charadrius melodus*)	M	RC	2	Hatching	62.00	34.00
Loegering 1992	Cage	Carnivores	Piping Plover (*Charadrius melodus*)	Isl	RC	3	Daily surv.	0.98	0.96
Niehaus et al. 2004	Cage	Carnivores	Western Sandpiper (*Calidris mauri*)	M	RC	1	Daily surv.	0.99	0.96
Nol and Brooks 1982	Cage	Gulls & mammals	Killdeer (*Charadrius vociferus*)	M	RC	1	Hatching	33.30	29.40
Post and Greenlaw 1989	Cage	Rice rat	Seaside Sparrow (*Ammodramus maritimus*)	M	RC	1	Hatching	47.60	5.90
Quinlan 1983	Fence	River otter	Fork-tailed Storm-petrel (*Oceanodroma furcata*)	Isl	RC	1	Hatching	84.00	35.30
Rimmer and Deblinger 1992	Cage	Mammals & birds	Least Tern (*Sterna antillarum*)	M	RC	2	Hatching	99.00	46.00
Rimmer and Deblinger 1990	Cage	Mammals & birds	Piping Plover (*Charadrius melodus*)	M	RC	3	Hatching	92.00	25.00
Yamaguchi et al. 2005	APN	Japanese marten	Varied Tit (*Parus varius*), Great Tit (*Parus major*)	M	BA	1	Hatching	43.90	29.33