

LETTER

Managing Invasive Mammals to Conserve Globally Threatened Seabirds in a Changing Climate

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Abstract

Invasive mammals are an ongoing threat at many seabird breeding locations, while impacts from climate change can occur over broad time scales. Combining management strategies for invasive mammal and climate change impacts is important for mitigating current threats and maximizing seabird survival into the future. We assessed all 713 islands with threatened seabirds for conservation importance, immediate benefits of three invasive mammal management actions, and risk of climate-change related flooding. Preventing invasions on the 397 islands without invasive mammals could benefit 72 seabird species. Invasive mammal eradication or localized action on 249 and 67 islands could benefit 71 and 46 seabird species, respectively. The long-term risk of flooding on the 713 islands was low (69%). Low-risk islands were concentrated where eradications or localized action were highlighted (75% and 100% of islands, respectively). These results inform management feasibility assessments and highlight rare opportunities to make significant contributions to seabird conservation.

Introduction

About 30% of seabird species are threatened with extinction, primarily due to invasive species (Townsend *et al.* 2011; Croxall *et al.* 2012). Most threatened seabirds breed on islands, with greater than 90% co-occurring with a threatening invasive species on at least one island (Spatz *et al.* 2014). Some of these islands have low elevations, and are the most vulnerable areas globally to climate-related increases in sea levels and storms (Nicholls & Cazenave 2010). Impacts include flooded nests, reduced breeding site availability, and potentially negated benefits from conservation actions (Bellard *et al.* 2013; Courchamp *et al.* 2014; Reynolds *et al.* 2015). While sea levels will increase over time, the threat of invasive mammals to seabirds is immediate, requiring direct attention (Croxall *et al.* 2012). To address the

threat of invasive mammals, eradications and localized control have occurred on islands globally, directly benefiting seabirds through positive demographic and distributional responses (Young *et al.* 2009; Jones *et al.* 2016; Luther *et al.* 2016). By removing a key threat, eradications can buffer seabirds from extinction through increasing seabird populations and conserving genetic diversity, which is a critical component of adaptability when facing global changes as well as for preserving global evolutionary history (Frankham 2005; Chambers *et al.* 2011; Jetz *et al.* 2014). Therefore, effective planning requires integration of invasive mammal management against the threat of longer-term exposure to climate change to ensure both immediate and long-term species persistence.

To determine the global scale of conservation opportunities for seabirds, Spatz *et al.* (2014) identified all islands on which globally threatened seabird species are known

to breed and determined if invasive mammals occurred on these islands. Here, we identify invasive mammal management scenarios to conserve threatened seabirds (classified as Critically Endangered, Endangered, and Vulnerable by BirdLife International for the International Union for the Conservation of Nature [IUCN] Red List), and examine the potential exposure of islands to sea level rise impacts. To do this, we: (1) score islands for their conservation importance to threatened and evolutionarily distinct seabirds; (2) identify where exposure to coastal flooding may impact conservation efforts; and (3) place islands into one of three portfolios that identifies the most urgent invasive mammal management needed: prevention (where invasive mammals are absent), eradication (whole-island) removal, or localized action (subisland control or removal) of invasives. For islands in the eradication management portfolio, we created two ranked lists that (1) maximized seabird importance (highlighting the most globally important projects for conserving threatened species), or (2) minimized the operational complexity of an eradication (highlighting projects that could be implemented at faster time scales). Our goal is to prompt conservation planning for threatened seabirds at transnational scales, by identifying near-term conservation actions and recognizing potential longer-term threats from sea level rise.

Methods

Characteristics of islands (i.e., size, location, presence of human populations, and invasive mammals; Supporting Information) with globally threatened breeding seabirds (BirdLife International 2012), hereafter, “seabirds,” are from the Threatened Island Biodiversity Database (Threatened Island Biodiversity Database Partners 2015) and described in Spatz *et al.* (2014).

Island exposure to flooding

The low-lying coastal zone, characterized by the topographic distribution of land adjacent to the sea, represents where physical exposure from climate change, such as flooding and sea level rise, will be most impactful (Woodroffe 2008; Nicholls & Cazenave 2010). This exposure potential on islands is hereafter referred to as “flooding risk” (Supporting Information). We used elevation data from Shuttle Radar Topography Mission with a resolution of 90 m horizontal and 1 m vertical (Rabus *et al.* 2003). We calculated the land below 5, 10 and 20 m elevation and compared it with total surface area for each island. Islands with >50% surface area below 5 or 10 m, or above 10 m, were classified as high, medium or

low flooding risk, respectively. When elevation profiles were not available (150 islands), we found maximum elevations of each island, and classified the islands as high, medium or low flooding risk when maximum elevation was <10, 11–20 or >20 m, respectively. We tested for differences in island characteristics against the flooding risk categories using Kruskal-Wallis (KW) rank sum tests.

Important islands for seabird conservation

We examined all islands with extant seabirds (97 species as 1,078 confirmed, probable, or potential breeding populations; Supporting Information). A seabird species breeding on an island was considered a single population. For each *species* (*s*), we calculated a Threatened Seabird (TS) score, by finding the product of its probability of extinction (“extinction risk”; *E*), relative endemism (“irreplaceability”; *I*), and relative evolutionary distinctiveness (“distinctiveness”; *D*)

$$TS_s = E \times I \times D.$$

Extinction risk (*E*) was scored as 0.005, 0.05, and 0.5 (Butchart *et al.* 2004), for the IUCN Red List categories of Vulnerable, Endangered, and Critically Endangered, respectively. Irreplaceability (*I*) is a relative measure of endemism (Margules & Pressey 2000), calculated as 1/the number of extant populations for each *species*. Evolutionary distinctiveness is a measure of contribution to global phylogenetic diversity (Isaac *et al.* 2007). We calculated relative distinctiveness (*D*), by dividing each species’ evolutionary distinctiveness score (EDGE 2014) by the greatest evolutionarily distinct score of all seabirds in our data set (28.418 ED for Peruvian Diving-petrel [*Pelecanoides garnotii*]). We ran sensitivity analyses to assess the impact of each score on species priorities (and subsequently island priorities; Supporting Information).

Seabird island importance score

We calculated a Seabird Island Importance (SII) score as a metric of seabird conservation benefit on the 713 islands with extant seabirds and known information on invasive mammals (Supporting Information). Each island received a relative rank based on SII score. A TS score was applied to each seabird species’ breeding population, then modified based upon that population’s breeding status (*P*). We summed the modified TS scores for all the species (*s*) on each island (*i*)

$$\sum_1^s TS_{s,i} \times P_{s,i}.$$

Each confirmed or probable breeding population received a full TS score. A potentially breeding population received 0.75 of its TS score to reduce weighting of populations with uncertain occurrence. We only included islands that supported extant seabird breeding populations but if these islands held other species that are now extirpated, the extirpated population received 0.5 of its TS score in recognition of the potential recovery of an extirpated population. We did not account for a nearby source population for that species.

Invasive mammal management portfolios

Each island was placed into an invasive mammal management portfolio, then examined for globally available island characteristics, including flooding risk. We used Kruskal-Wallis (KW) rank sums to test for differences in SII scores between portfolios.

Prevent invasions

We identified islands where invasive mammals are absent and policy actions (e.g., biosecurity) can proactively prevent mammal invasion (Broome 2007; Simberloff *et al.* 2013).

Eradication

We identified islands where ≥ 1 invasive mammal species are present and complete removal of an invasive mammal species may be achievable. This included islands where an eradication is underway, or managing repeated incursion responses, is ongoing (Supporting Information). To identify where eradication may be achievable, we examined thresholds of three globally recognized criteria (Supporting Information) that influence eradication operation complexity—invasive mammal type (e.g., cat, rat), island area and human population size (Oppel *et al.* 2011; Veitch *et al.* 2011)—referenced from successful mammal eradication efforts to date (DIISE 2015) and expert opinion.

Islands with ≥ 1 invasive mammal considered for eradication were subsequently scored in two ways, resulting in two ranked lists. First, we applied the SII score to each island to understand where eradication would benefit the most important seabirds, highlighting the most important projects at a global scale, regardless of operational complexity. The second score was based on basic island characteristics influencing complexity of eradication operations (Eradication Complexity [EC] score), for which we

then ranked islands for minimized complexity, to identify projects that could proceed at faster time scales than others. The EC score was calculated as

$$EC_i = ME_i \times MR_i \times HI_i \times A_i.$$

For each island (*i*), we calculated the product of the proportion of all invasive mammal species that could be potentially eradicated (*ME*), a weighted number of invasive mammal species remaining (*MR*), the number of human inhabitants present (log scale; *HI*) and island size relative to the smallest island (*A*; Table S2). We highlighted top-scoring priority islands (the upper 75th percentile of island scores) in each list.

Localized action

We identified islands with invasive mammals where eradication thresholds were exceeded for all invasive mammal types present. These islands were considered for subisland management, such as local control or fencing, to eliminate or reduce threat at a colony scale (Parkes & Murphy 2003).

Results

Seabird and island scores

Christmas Island Frigatebird (*Fregata andrewsi*) and New Zealand Storm-petrel (*Oceanites maorianus*) received the highest TS scores (Table S3; Data Supplement). Christmas (Australia) and Hauturu-o-Toi (New Zealand) islands received the highest SII scores (Figure 1). Sixteen islands ranked in the upper 97th percentile of SII scores (Table 1). All scores and sensitivity results are described in the Supporting Information and Table S3.

Island exposure to sea level rise

Flooding risk was low on 490 islands (69%; Figure 2) that support 798 populations (74%) of 92 (95%) seabird species, including 13 (81%) Critically Endangered species breeding exclusively on these islands. Low-risk islands were larger (KW = 190.5, *df* = 2, *P* < 0.001), contained more seabirds (KW = 12.6, *df* = 2, *P* = 0.002), and received higher SII scores (KW = 10.7, *df* = 2, *P* = 0.005) than higher-risk islands. Forty-two seabirds (43%) of 280 populations (26%) occurred on ≥ 1 island with high (159, 15%) or medium (121, 11%) risk. Seven species had $\geq 50\%$ of their extant populations from these islands and three species were restricted to these islands (Table 2).

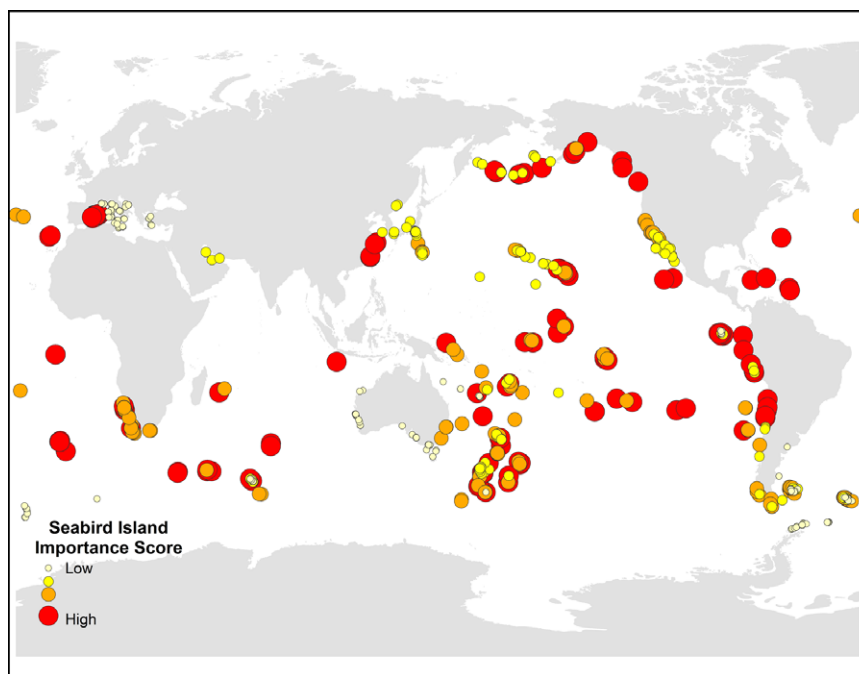
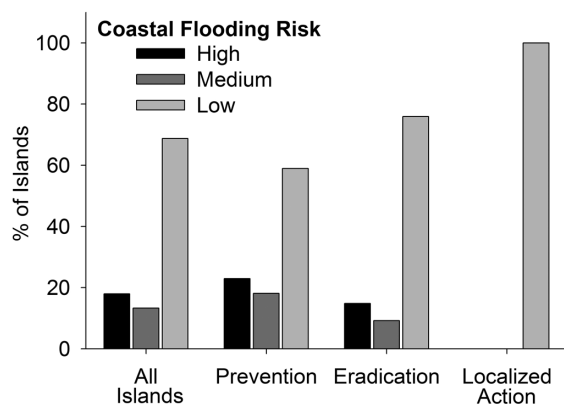


Figure 1 The worldwide distribution of islands with 97 threatened seabirds, scored by their IUCN Red List category, endemism, and contribution to global evolutionary distinctiveness (SII). Dots are scaled by the quantile distribution of scores whereby the largest dots represent the upper 75th percentile of scores and the smallest dots represent the lower 25th percentile of scores.



All Islands and Invasive Mammal Management Portfolios

Figure 2 The percent of islands within each conservation management portfolio (prevention, eradication, localized action), broken up by high, medium, or low coastal flooding risk. "All Islands" represents the cumulative total of seabird islands analyzed (713) and the percent of islands within each flooding risk category.

Conservation management portfolios

Prevention

Invasive mammals were absent on 397 (56%) islands that support 623 populations of 72 (74%) seabirds (10 species were restricted to these islands; Data Supplement).

Islands were in 31 countries, primarily New Zealand, the United Kingdom (Overseas Territories), the United States and Chile, and were mostly uninhabited (372 islands, 94%). Seventy-three percent of all higher flooding risk islands were concentrated in this portfolio: 163 islands (41%) were high- or medium-risk. Three species had $\geq 50\%$ of their extant breeding populations on these islands: Ascension Frigatebirds (*F. aquila*), Cape Gannets (*Sula capensis*), and Bank Cormorants (*Phalacrocorax neglectus*).

Eradication

Invasive mammals were present on 249 (35%) islands that fell within our eradication thresholds, supporting 339 populations of 71 (73%) seabird species. Twenty-nine seabird species had half of their islands in this portfolio and seven were restricted to these islands. Islands were in 34 countries, primarily Italy, Japan, New Zealand, and the United States and were minimally inhabited (148 [59%] uninhabited, 52 [21%] with 1-100, and 32 [13%] with 101-1,000 people). The most common invasive mammal types were *Rattus* sp. (rat) on 179 islands, and *Mus* sp. (mouse) and *Felis* sp. (cat) on 87 islands each. Sixty islands (24%) had high or medium flooding risk (Figure 2) with only one seabird breeding

Table 1 Seabird Island Importance (SII) scores for the 16 top-scoring islands (upper 97th percentile). These islands represent important conservation areas for conserving globally threatened and evolutionarily distinct seabird species (TS score), regardless of invasive mammal status.

Island	Country or territory ^a	SII Score	Common name ^b	2012 IUCN Red List category ^b	TS score
Christmas	CXR	0.432	Abbott's Booby	EN	0.934
			Christmas Island Frigatebird	CR	11.339
Little Barrier	NZL	0.314	Cook's Petrel	VU	0.019
			New Zealand Storm-petrel	CR	8.882
			Parkinson's Petrel	VU	0.018
Chatham (Rekohu)	NZL	0.136	Antipodean Albatross	VU	0.005
			Chatham Islands Shag	CR	0.701
			Chatham Petrel	EN	0.140
			Erect-Crested Penguin	EN	0.031
			Magenta Petrel	CR	2.952
			Pitt Island Shag	EN	0.029
New-Ireland	PNG	0.133	Beck's Petrel	CR	3.788
Gau	FJI	0.125	Collared Petrel	VU	0.003
			Fiji Petrel	CR	3.548
Reunion	REU	0.124	Barau's Petrel	EN	0.299
			Mascarene Petrel	CR	3.222
Amsterdam	ATF	0.124	Amsterdam Albatross	CR	3.381
			Indian Yellow-nosed Albatross	EN	0.041
			Northern Rockhopper Penguin	EN	0.053
			Sooty Albatross	EN	0.039
Jamaica	JAM	0.097	Jamaica Petrel	CR	3.676
Española (Hood)	ECU	0.096	Waved Albatross	CR	2.717
Plata	ECU	0.096	Waved Albatross	CR	2.717
Inaccessible	SHN	0.072	Atlantic Petrel	EN	0.095
			Atlantic Yellow-nosed Albatross	EN	0.048
			Northern Rockhopper Penguin	EN	0.053
			Sooty Albatross	EN	0.039
			Spectacled Petrel	VU	0.045
			Tristan Albatross	CR	1.780
			Gough	SHN	0.071
Gough	SHN	0.071	Atlantic Yellow-nosed Albatross	EN	0.048
			Northern Rockhopper Penguin	EN	0.053
			Sooty Albatross	EN	0.039
			Tristan Albatross	CR	1.780
Socorro	MEX	0.060	Townsend's Shearwater	CR	1.693
Clarión	MEX	0.060	Townsend's Shearwater	CR	1.693
Kodiak	USA	0.040	Kittlitz's Murrelet	CR	1.102
			Marbled Murrelet	EN	0.034
Adak	USA	0.040	Kittlitz's Murrelet	CR	1.102
			Marbled Murrelet	EN	0.034

^aBased on ISO Alpha-3 codes (International Organization for Standardization 2016).

^bSeabird taxonomy and IUCN Red List category (CR = Critically Endangered, EN = Endangered, VU = Vulnerable) are from BirdLife International (2012).

almost exclusively (80%) on these islands (Bermuda Petrel, *Pterodroma cahow*).

All islands scored and ranked for SII and operational EC are in the Data Supplement (see also Figure 3). Only three islands were identified as priority islands in both data sets (Table 3). The SII priorities included 65 islands (SII score ≥ 0.001) in 16 countries and supported 128 populations of 51 seabird species; 8 species were restricted to these islands. Islands were large

and variable in size (mean \pm SD = 76.5 \pm 150.7 km²), 54% uninhabited and 34% with 1-1,000 people, and had low flooding risk (77%). Based on eradication thresholds used, all invasive mammals could be potentially eradicated from 51 (80%) islands. Islands contained a median of two invasive mammal species (maximum = 12).

The EC priorities included 63 islands (EC score ≥ 0.005) in 21 countries and supported 67 populations of 22

Table 2 The 42 threatened seabird species on islands with high or medium risk of exposure to coastal flooding, including 3 Critically Endangered species and 7 species found only on these islands.

Scientific Name ^a	Common Name ^a	IUCN Red List Category ^a	High Risk	Medium Risk	Total at Risk
<i>Phalacrocorax onslowi</i>	Chatham Islands Shag	CR	40%	0%	40%
<i>Puffinus mauretanicus</i>	Balearic Shearwater	CR	17%	28%	44%
<i>Sterna bernsteini</i>	Chinese Crested Tern	CR	29%	14%	43%
<i>Eudyptes sclateri</i>	Erect-crested Penguin	EN	13%	13%	27%
<i>Megadyptes antipodes</i>	Yellow-eyed Penguin	EN	0%	6%	6%
<i>Nesofregatta fuliginosa</i>	White-throated Storm-petrel	EN	38%	6%	44%
<i>Oceanodroma homochroa</i>	Ashy Storm-petrel	EN	6%	24%	30%
<i>Pelecanoides garnotii</i>	Peruvian Diving-petrel	EN	7%	0%	7%
<i>Phalacrocorax featherstoni</i>	Pitt Island Shag	EN	25%	0%	25%
<i>Phalacrocorax neglectus</i> *	Bank Cormorant	EN	59%	15%	73%
<i>Pterodroma alba</i>	Phoenix Petrel	EN	47%	7%	53%
<i>Pterodroma cahow</i>	Bermuda Petrel	EN	80%	20%	100%
<i>Spheniscus demersus</i> *	African Penguin	EN	44%	28%	72%
<i>Spheniscus mendiculus</i>	Galapagos Penguin	EN	13%	25%	38%
<i>Sterna lorata</i> *	Peruvian Tern	EN	100%	0%	100%
<i>Thalassarche melanophrys</i>	Black-browed Albatross	EN	3%	3%	7%
<i>Diomedea exulans</i>	Wandering Albatross	VU	11%	22%	33%
<i>Eudyptes chrysocome</i>	Southern Rockhopper Penguin	VU	3%	4%	7%
<i>Eudyptes chrysolophus</i> *	Macaroni Penguin	VU	7%	8%	15%
<i>Eudyptes pachyrhynchus</i>	Fiordland Crested Penguin	VU	7%	0%	7%
<i>Eudyptes robustus</i>	Snares Crested Penguin	VU	0%	25%	25%
<i>Fregata aquila</i>	Ascension Frigatebird	VU	50%	0%	50%
<i>Larus fuliginosus</i>	Lava Gull	VU	13%	13%	27%
<i>Leucocarbo campbelli</i>	Campbell Island Shag	VU	25%	0%	25%
<i>Leucocarbo carunculatus</i>	New Zealand King Shag	VU	11%	11%	22%
<i>Leucocarbo chalconotus</i>	Stewart Island Shag	VU	0%	8%	8%
<i>Leucocarbo ranfurlyi</i>	Bounty Islands Shag	VU	15%	15%	31%
<i>Oceanodroma monteiroi</i>	Monteiro's Storm-petrel	VU	0%	20%	20%
<i>Phalacrocorax nigrogularis</i> *	Socotra Cormorant	VU	10%	0%	10%
<i>Phoebastria albatrus</i>	Short-tailed Albatross	VU	0%	29%	29%
<i>Phoebastria nigripes</i>	Black-footed Albatross	VU	15%	24%	38%
<i>Procellaria aequinoctialis</i>	White-chinned Petrel	VU	21%	16%	37%
<i>Puffinus yokouan</i> *	Yelkouan Shearwater	VU	4%	7%	11%
<i>Rissa brevirostris</i>	Red-legged Kittiwake	VU	7%	20%	27%
<i>Spheniscus humboldti</i> *	Humboldt Penguin	VU	6%	10%	16%
<i>Sterna nereis</i> *	Fairy Tern	VU	24%	11%	35%
<i>Sula capensis</i>	Cape Gannet	VU	50%	50%	100%
<i>Synthliboramphus craveri</i>	Craveri's Murrelet	VU	5%	14%	19%
<i>Synthliboramphus hypoleucus</i>	Xantus's Murrelet	VU	4%	11%	15%
<i>Synthliboramphus wumizusume</i> *	Japanese Murrelet	VU	10%	7%	17%
<i>Thalassarche chrysostoma</i>	Grey-headed Albatross	VU	9%	6%	16%
<i>Thalassarche salvini</i>	Salvin's Albatross	VU	8%	8%	17%

^aSeabird taxonomy and IUCN Red List category (CR = Critically Endangered, EN = Endangered, VU = Vulnerable) are from BirdLife International (2012).

*Species that may also breed on continents; continental sites were not included in our analysis.

seabird species. Islands were small (mean \pm SD = 0.1 \pm 0.1 km²), uninhabited (100%), and 43% were at low flooding risk (33% of islands at high risk). Based on our eradication thresholds, all invasive mammals could be potentially eradicated from these islands. Islands contained a median of one invasive mammal species (maximum = 4).

Localized action

Invasive mammals were on 67 (9%) islands that did not meet eradication threshold criteria (Data Supplement). SII scores were highest in this portfolio (KW = 21.5, df = 2, $P < 0.001$). These islands supported 116 populations of 46 (47%) seabird species; 11 species from 12 islands

Table 3 The 25 top-scoring islands in the Eradication Management Portfolio, ranked for (A) maximized seabird conservation importance (SII score) or (B) minimized operational complexity of eradicating invasive mammals (EC score). Ranks represent island scores. When ranks were equal (same SII or EC score) we listed islands in alphabetical order.

A. Islands ranked by the SII score						
SII rank	Island	Country or territory ^a	No. of extant seabird species ^b	Coastal flooding hazards	No. of invasive mammals present ^c	% Mammals that can be eradicated
1	Chatham (Rekohu)	NZL	6	Low	12	8%
2	Gau	FJI	2	Low	7	29%
3	Amsterdam	ATF	4	Low	5	100%
4	Plata	ECU	1	Low	2	100%
5	Gough	SHN	5	Low	1	100%
6	Clarión	MEX	1	Low	1	100%
6	Socorro	MEX	1	Low	2	100%
7	Tristan da Cunha	SHN	5	Low	6	100%
8	Floreana	ECU	2	Low	6	67%
9	San Cristobal	ECU	2	Low	10	50%
10	Jongdao 1	TWN	1	Medium	1	100%
10	Tiejien	TWN	1	Low	1	100%
11	Santa Maria	CHL	2	High	1	100%
12	Mantou shan	CHN	1	Low	1	100%
12	Yaque shan	CHN	1	Low	1	100%
13	Pitt	NZL	4	Low	9	78%
14	Aire	ESP	1	High	1	100%
14	Conillera	ESP	1	Low	3	100%
14	Dragonera	ESP	1	Low	1	100%
14	Espalmador	ESP	1	High	6	100%
14	Espartar	ESP	1	Low	1	100%
14	Formentera	ESP	1	Low	8	13%
14	Tagomago	ESP	1	Low	4	100%
15	Saint-Paul	ATF	3	Low	1	100%
16	Henderson	PCN	2	Low	1	100%
B. Islands ranked by the EC score						
EC rank	Island	Country or territory ^a	No. of extant seabird species ^b	Coastal flooding hazards	No. of invasive mammals present ^c	% Mammals that can be eradicated
1	Paryadin Peninsula North Island 2	SGS	1	Low	1	100%
2	Paryadin Peninsula South Island 3	SGS	2	High	1	100%
3	Paryadin Peninsula North Island 3	SGS	1	Low	1	100%
4	Ram	AUS	1	High	4	100%
5	Green Rock	BMU	1	High	2	100%
6	Logie (Lougie)	ECU	1	High	2	100%
7	Horn Rock	BMU	1	High	2	100%
8	Tiejien	TWN	1	Low	1	100%
9	Sanbondake (South)	JPN	1	Low	1	100%
10	Jongdao 1	TWN	1	Medium	1	100%
11	Inner Pear Rock	BMU	1	High	2	100%
11	Yaque shan	CHN	1	Low	1	100%
12	Motone	JPN	1	Low	1	100%
13	Long Rock	BMU	1	High	2	100%
14	Veliki Rutvenjak	HRV	1	High	1	100%
15	Eboshijima	JPN	1	Medium	1	100%
16	Fungus Rock	MLT	1	Low	2	100%
17	Makarac	HRV	1	High	1	100%
18	Rolla	NZL	1	Low	3	100%
19	Tarakoi	PYF	1	Medium	1	100%
20	Wharekakahu	NZL	1	Medium	1	100%

Continued

Table 3 Continued

B. Islands ranked by the EC score						
EC rank	Island	Country or territory ^a	No. of extant seabird species ^b	Coastal flooding hazards	No. of invasive mammals present ^c	% Mammals that can be eradicated
21	Onohara	JPN	1	High	1	100%
21	Atire	NCL	1	High	1	100%
22	Minamitori	JPN	1	Low	1	100%
23	Imotojima Torishima	JPN	1	Medium	1	100%

^aBased on ISO Alpha-3 codes (International Organization for Standardization 2016).

^bSeabird populations were considered “extant” when they were documented as either Confirmed, Probable, or Potential Breeding (see Supplemental Information for more details).

^cAn invasive species was considered as “present” if it was confirmed or suspected on an island (including if an eradication was underway or incursion responses were ongoing, see Supplemental Information for more details).

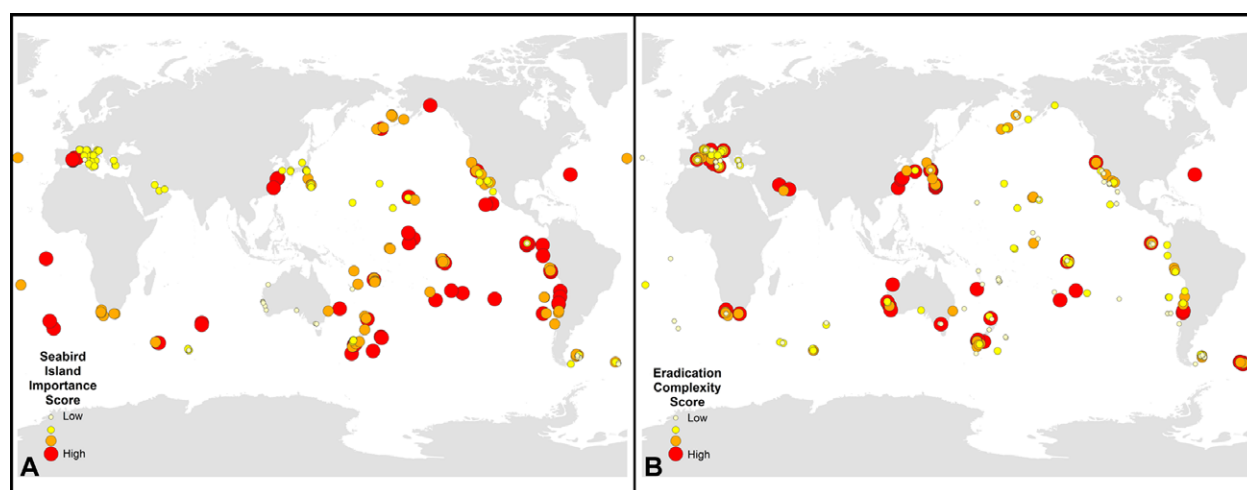


Figure 3 The two ranked lists of islands for invasive mammal eradication on islands with globally threatened seabirds. Dots are scaled by the quantile distribution of scores based on the (A) SII score that maximizes the conservation benefit of protecting seabird species that are most threatened and evolutionarily unique and the (B) EC score that minimizes the operational complexity of an eradication.

were restricted to this portfolio. These islands were large (mean \pm SD = 9,561 \pm 26,903 km²), inhabited (62 islands [93%]; 76% of which supported >1,000 people), with low flooding risk (Figure 2).

Discussion

We focused on immediate and long-term threats to seabirds on islands: invasive mammals, a driver of current seabird extinctions that can often be mitigated with demonstrated benefits for seabirds, and the exposure of islands to coastal impacts from climate change, a threat that can affect seabird conservation over longer time frames (Courchamp *et al.* 2003; Croxall *et al.* 2012; Jones *et al.* 2016). We investigated seabirds and islands at the global level, reflecting the multinational distributions of many seabirds, and a necessary scale for coordinated and

effective conservation planning. Our results highlight important islands and species globally for conservation actions from which more detailed island or species-specific feasibility assessments can be built.

Important islands for seabird conservation

We highlighted the conservation importance of islands with the most threatened seabirds and with the highest potential for genetic diversity loss. Invasive mammals can have profound effects on both species survival and the overall maintenance of genetic diversity, which is critical for adaptability in the face of global changes (Frankham 2005; Gasc *et al.* 2010) as well as for preserving global evolutionary history (Jetz *et al.* 2014). Our results often highlighted Critically Endangered species with high evolutionary distinctiveness scores, such as the Christmas

Island Frigatebird and New Zealand Storm-petrel (Critically Endangered, single-island endemic, and evolutionarily distinct species) and their islands, Christmas and Hauturu-o-Toi (previously, Little Barrier Island). In some cases, less threatened but highly endemic and evolutionarily distinct species, like the Endangered Abbott's Booby and Vulnerable Ascension Frigatebird, received high scores and their islands were also highlighted for their importance to global seabird conservation (Table S1). Prioritizing conservation of these threatened and evolutionarily distinct species can prevent imminent extinctions while maintaining important genetic diversity (Isaac *et al.* 2007; Jetz *et al.* 2014).

Island exposure to sea level rise

A fine-scale understanding of the risk to islands from climate change depends on many biophysical factors (Nicholls & Cazenave 2010; Slangen *et al.* 2014). However, these data are lacking or inconsistent for most of the world's islands. Our approach, using elevation as a proxy for risk of flooding from sea level rise (Woodroffe 2008), was a coarse first step toward inferring physical coastal impacts from climate change, and enabled the integration of potential long-term impacts from flooding alongside current immediate impacts to seabirds from invasive mammals. We found that most threatened seabirds breed on islands with sufficient elevation to be at low risk of exposure to impacts from sea level rise. This is encouraging for seabird conservation, suggesting that tackling invasive mammal threats can be a long-term solution for many threatened seabird populations. However, we did not account for where seabird colonies are located on islands, which could result in over- or underestimates of exposure. Some seabirds nest on high-elevation cliffs or in mountain forests, making them less sensitive to coastal impacts, while others nest along coastlines and can be sensitive to flooding (Schreiber & Burger 2002). To address these data gaps, next steps should include species-specific climate vulnerability assessments at the island or colony level, including consideration of species' sensitivity and adaptability to change (e.g., Foden *et al.* 2013).

Twenty-five percent of threatened seabird populations in our study were on low elevation islands (223 islands) and may be exposed to sea level rise impacts (Table 3). Most (73%) of these islands were free of invasive mammals and the remaining were included in our eradication portfolio, typically ranked highly for minimized eradication complexity. These islands may represent only interim refuges for threatened seabirds, yet are important short-term opportunities where managers can offset threats from invasive mammals and reduce extinction risk.

Invasive mammal management portfolios

Prevention

Through a combination of biogeographic good fortune, successful invasive mammal eradication efforts on 82 islands (DIISE 2015), and ongoing biosecurity programs (e.g., Hauturu-o-Toi Island [New Zealand Department of Conservation 2014]), 55% of islands supporting extant threatened seabird populations were free of invasive mammals. These islands have ≥ 1 breeding population of 74% of threatened seabird species, including 10 species breeding exclusively on these islands. Biosecurity is a proactive approach to protecting islands from invasions (Broome 2007). If not already in place, risk assessments of both anthropogenic and natural reinvasion risk are critically important for conserving these islands, their breeding seabirds, and endemic species (Harris *et al.* 2012).

Eradication

Eradications on 249 islands (79% of islands with threatened seabirds and invasive mammals) would conserve populations of 73% of threatened seabird species. Our two ranked sets of islands, highlighting either globally important projects to conserve seabirds or islands with assumed lower eradication complexity, were inversely related. Many of the most important islands for conserving threatened seabirds tend to be larger and have more invasive mammal species and human inhabitants. When eradication complexity was minimized, higher-ranked islands were small islets offshore larger islands or mainland areas, uninhabited, and often low elevation with only one invasive mammal species.

While conservation efforts on the islands in the two ranked lists will likely require different approaches (i.e., due to increased operational complexity on larger islands or risk of reinvasion on small offshore islands), significant conservation opportunities exist. For example, three islands ranked highly in both sets conserve some of the world's most threatened seabirds (e.g., Critically Endangered Chinese Crested Tern [*Sterna bernsteini*]) and represent relatively straight forward eradication opportunities. As another example, four islands (Gough, Amsterdam, Plata, and Clarion) collectively support nine globally threatened, evolutionarily distinct seabird species. While these islands are relatively large, they are uninhabited by people and at low flooding risk, highlighting that benefits gained from eradicating invasive mammals on these islands may be sustained over long time scales.

Island area and human population size are two of the most useful criterion available globally for identifying potential eradication opportunities to conserve seabirds

at both global and regional scales (e.g., Brooke *et al.* 2007; Capizzi *et al.* 2010; Harris *et al.* 2012; Dawson *et al.* 2014). However, we recognize that these metrics are not the sole determinants of eradication feasibility, and that not all islands identified here will be deemed feasible with further assessment. Next steps include island-specific and archipelago-wide conservation assessments, including evaluations of ecosystem and species-specific threats and benefits, social, political and economic eradication feasibility, reinvasion risks, stakeholder valuation, and design of eradication plans (Zavaleta *et al.* 2001; Courchamp *et al.* 2003; Murdoch *et al.* 2007).

Localized action

We found that 8% of islands with invasive mammals exceeded our conservative thresholds for achievable whole-island invasive mammal eradications. Because the distribution of seabirds here is not island-wide, localized action, such as through predator-proof fencing or invasive species control, may be appropriate (Parkes & Murphy 2003; Luther *et al.* 2016). These subisland invasive mammal management actions are critically important for several of the most threatened and evolutionarily distinct seabird species, including 11 restricted to these islands (e.g., Mascarene Petrel [*Pseudobulweria aterrima*] on Reunion Island). Yet, while these actions are effective, they often require ongoing resources (Hodges & Nagata 2001), thus long-term adaptive approaches, such as translocations to invasive-free islands, may be important to consider for some seabird species in this portfolio. Finally, several islands in this portfolio are currently undergoing invasive mammal eradication feasibility assessments (DIISE 2015; Supplemental Information), highlighting that advances in eradication techniques will open up new opportunities for seabird conservation in the future.

Conclusions

We identified 713 islands globally where invasive mammal prevention, eradication, or localized action can potentially conserve populations of Critically Endangered, Endangered, or Vulnerable seabirds. Our analysis also identified islands where coastal impacts from sea level rise, such as flooding, could impact the long-term effectiveness of these conservation actions. While some species are at risk of losing nests or habitat from flooding, sea level rise does not appear to be a significant threat for 75% of globally threatened seabirds. With appropriate climate adaptation plans in place alongside invasive mammal management, the long term conservation of seabirds

represents a rare opportunity to make a significant contribution to global biodiversity conservation.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Table S1. Area and human population size thresholds for invasive mammal eradications used in our analyses

Table S2. Variables and metrics used in the EC score.

Table S3. The 97 globally threatened seabird species ordered by their TS rank and the sensitivity of this rank to probabilities of extinction, relative endemism, and evolutionary distinctiveness

Table S4. Sensitivity results: correlations between extinction risk probabilities against irreplaceability scores

Data Supplement: SII scores for all 713 islands and results from the invasive mammal eradication ranking.

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