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Using meta-population models to guide conservation action

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ABSTRACT

Biodiversity conservation is limited by resources, data, and time for execution. To maximize efficacy, it is best if conservation plans are strategically evaluated for cost, feasibility, and likely impact prior to implementation. We present a framework to systematically examine the likely impact of proposed conservation plans for threatened taxa. As a case study of this framework we use the national Action Plan for Seabird Conservation in New Zealand and 27 threatened seabirds identified for conservation interventions. To evaluate impact, we applied a recently developed seabird meta-population viability analysis model (seabird mPVA) that employs the most current population and adjustable demographic data to assess threatened seabird viability at a global scale under various management scenarios. This publicly available, web-based tool is intended to meet the needs of threatened seabird managers at the initial phase of conservation planning. We used the seabird mPVA to model population trends and potential seabird viability gains from conservation actions that include: bycatch mitigation, invasive species removal, and seabird translocation prescribed in the action plan for individual species. Our model's ranking of New Zealand seabirds by current quasi-extinction vulnerability roughly correlated with the seabirds' IUCN Red List status and New Zealand Threat Classification System. We found modeled conservation impact of proposed actions and assigned priority to be generally positively correlated, but variable in magnitude. If all prescribed conservations actions were implemented, our model predicted significant mitigation of quasi-extinction risk for nine species (Antipodean Albatross, Auckland Island Shag, Black-fronted Tern, Fairy Tern, Rough-faced Shag, Northern Royal Albatross, Pitt Island Shag, Stewart Island Shag, Yellow-eyed Penguin). This approach, and our model, can be adapted to other taxonomic groups to provide a consistent framing for the prioritization of species for conservation investment and predictions about the benefits of specific conservation actions for those species.

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1. Introduction

Biodiversity loss imperils ecosystem function and services (Hooper et al., 2012). Still, conservation goals, such as the international Aichi Biodiversity Targets are largely unmet and trends for biodiversity loss are steady or increasing (Krug et al.,

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2014; El-Sheikh, 2018). Worldwide, conservation plans are underfunded and tied to national wealth rather than biodiversity and threats (Waldron et al., 2013, 2017).

Species assessments of extinction risk are a critical tool to help direct policy and legal protections, but they are generally poorly funded, often outdated, and grossly backlogged. For instance, in the United States, the Endangered Species Act provides legal protection for threatened species. However, over 500 species potentially warrant protection but await decisions on protections and decision times average 12 years (Greenwald et al., 2019; Puckett et al., 2016). Internationally, insufficient resources for the IUCN Red List of Threatened Species delay many species assessments, threatening their relevance to conservation planning (Rondinini et al., 2014). Moreover, many species assessed as threatened lack recovery plans, including 46% of threatened (critically endangered, endangered, or vulnerable) seabird species (IUCN, 2020). Thus, managers are limited by underfunding, inadequate data on population trends and specific threats, and incomplete biological, legal, and policy frameworks to prioritize species and develop strategic conservation plans. Given this, successful conservation planning requires a data-driven approach to testing threatened species recovery plans.

One method to assess the current status of threatened species and the potential efficacy of recovery plans prior to implementation is through population viability analysis (PVA). PVAs have played an important role in informing future population trajectories, conservation policy, and potential actions (Morris and Doak, 2002; Finkelstein et al., 2010; Lindenmayer et al., 1993). For example, through meta-population viability analysis (mPVA), researchers determined that the endangered piping plover depends on human-created habitats to rebound from flooding disturbances (Catlin et al., 2015). While PVAs have been widely adopted for single species, they have not been taken to scale across taxonomic groups or regions, perhaps because PVAs are often difficult and time consuming to develop and run.

We developed a comprehensive, generalizable, mPVA model (hereafter seabird mPVA) that predicts relative quasi-extinction risk in a consistent way across an entire group of species with similar life histories, and the predicted impacts of different conservation actions for those species. The freely accessible (https://nhydra.shinyapps.io/mPVA1/), menu-driven online model draws from a comprehensive, though by no means complete, database of species life history traits, and uses phylogenetically weighted data from closely related species to fill demographic data gaps. Here we apply our seabird mPVA to threatened New Zealand seabirds to establish baseline risk and test the efficacy of proposed management actions. We use the seabird mPVA to project the metapopulation trajectories of 27 threatened seabird species under a baseline (no-intervention) scenario and various proposed management scenarios. This allows us to determine relative extinction risk among species and estimate the relative efficacy of prescribed actions within species.

As the most threatened marine taxonomic group (IUCN, 2020), seabirds provide a useful trial of our mPVA approach. While the seabird mPVA is equipped to model 99 well-documented, threatened seabird species, we limit this study to the 27 threatened seabirds that breed in New Zealand and have prescribed management interventions that can be analyzed with our model. New Zealand is an ideal location to trial our framework for several reasons. First, it is a hotspot for seabird diversity, hosting 96 of the world's 346 seabird species, 33 of which are endemic to New Zealand (Croxall et al., 2012). Second, strategic conservation is urgently needed with 39% of New Zealand seabird species and 82% of its endemic seabird species are classified as threatened (critically endangered, endangered, vulnerable) by the IUCN Red List (Robertson et al., 2017; IUCN, 2020). Third, New Zealand's offshore islands rank highest for global seabird conservation opportunities when considering the probabilities of extinction, relative endemism, and evolutionary distinctiveness of breeding seabirds species (Spatz et al., 2017). Finally, New Zealand developed a national action plan for all threatened New Zealand seabirds (Taylor, 2000). The Action plan for seabird conservation in New Zealand (NZ Action Plan) describes the distribution, population size, conservation status, threats, past conservation actions, future research priorities, and proposes conservation actions for every threatened New Zealand seabird.

Seabirds are impacted by a wide range of threats, including human disturbance, harvest, invasive species, habitat loss, commercial fisheries bycatch and pollution (Croxall et al., 2012). The NZ Action Plan prescribes specific interventions to offset these, including: establishing new colonies, mitigating bycatch mortality, removal of invasive predators, and measures to increase survival at certain life stages. Our seabird mPVA was designed with the flexibility to model such conservation intervention scenarios. Users may adjust population distributions to simulate translocations, adjust at-sea mortality, remove specific invasive species' effects, as well as adjust vital rates across life stages. Here, we use our seabird mPVA to examine the predicted benefits of each intervention proposed in the NZ Action as a means to model potential benefit before investing the time and resources required for implementation. Further, we examine whether the priority assigned to intervention scenarios correlated with modeled viability gains. We additionally compare baseline projected quasi-extinction risk to current national and global threat assessments to identify mismatches between these approaches. While we limit this study to threatened New Zealand seabirds, our seabird mPVA can readily be applied to all threatened seabirds. Likewise, this framework for systematic review of conservation plans could be replicated within other threatened taxa.

2. Methods

2.1. Seabird mPVA

The seabird mPVA is a spatially explicit and demographically structured approach to evaluate seabird population viability in the context of current distribution, abundance, trends and multiple threats. The seabird mPVA draws on published seabird vital rates data (UCSC, 2020) to model demographic transitions and project future trends for populations of threatened seabirds, while accounting for meta-population structure of geographically distributed (but demographically linked) breeding colonies

and incorporating information on current trends and spatially-explicit threats. The seabird mPVA is based around a stagestructured projection matrix (Caswell, 2001). To ensure model generality across many different life history patterns (Desholm, 2009) we described demographic structure in terms of three broad life history stages: 1) sub-adults, 2) breeding adults, and 3) non-breeding adults. Spatial structure is incorporated by embedding demographic matrices for semi-discreet sub-populations (generally islands or island groups) within a larger meta-matrix structure representing the dynamics of the entire species. The advantage of including spatial and demographic structure in our model is that the impacts of various threats (invasive species, fisheries bycatch) are both spatially explicit and stage-specific, and thus the conservation benefits of mitigation efforts (such as removal of invasive species, fishing regulations, etc.) can be best-evaluated by modeling their effects on the appropriate demographic stages and/or sub-populations, and then translating these into species-level impacts (Desholm, 2009).

The seabird mPVA was parameterized using publicly available data contained in the IUCN Red List of Threatened Species version 2020.2 (IUCN, 2020) and additional data contained in the Threatened Island Biodiversity Database (TIB Partners, 2018), literature-reported values of seabird vital rates, and solicited expert opinion (UCSC, 2020). We adopted a Bayesian approach for estimating vital rates. Specifically, for each focal species we compiled published estimates of each demographic parameter required for the model, as well as uncertainty measures (standard errors) for these estimates. We weighted all published data by taxonomic relatedness between the focal species and the species for which the data originated. The combined distributions of existing parameter estimates were treated as prior distributions, which could be updated by comparing population projections generated from these priors with reported data on trends derived from the IUCN Red List (IUCN, 2020). For species in which there were only qualitative descriptions of current population trends, we allocated modal lambda values of 1.02, 1.00, 1.00, and 0.98 for Increasing, Unknown, Stable, and Decreasing status, respectively (with uncertainty distributions around these modal values). To update priors, we used Markov chain Monte Carlo (MCMC) methods to find the combination of values of demographic parameters most likely to produce the observed trends, resulting in posterior distributions for each parameter.

We expanded the base seabird mPVA model to incorporate additional information on specific threats, including the effects of invasive species and at-sea threats such as fisheries bycatch. To estimate the demographic effects of invasive species on baseline vital rates, we compared published time series of seabird abundance estimates at islands where invasive species occur vs. islands where they are absent, as well as before-after trends for islands where invasive species were removed (Jones et al., 2008). We employed a proportional hazards formulation to combine the additional hazards associated with invasive species with baseline survival rates. Log hazards were calculated using a function that included covariates for invasive type, nesting type, body size, island size, and number of co-occurring invasive species (allowing for compensatory mortality at islands with > 1 invasive species present). We used MCMC methods to find the hazard function parameters (in conjunction with baseline demographic parameters) most likely to produce the observed reductions in growth rates.

We used the parameterized seabird mPVA to project population dynamics of threatened and endangered seabirds, accounting for environmental stochasticity and parameter uncertainty, and with starting abundances initialized using the most recent IUCN Red List status reports. Management actions were evaluated by simulating the effects on vital rates (e.g. in the case of invasive species removal actions, we simply removed the additional hazards associated with the invasive), and by comparing the distributions of model projections with and without the management action. Further description of the seabird mPVA mechanics can be found in Tinker et al., 2021, under review.

2.2. Application of the seabird mPVA to the NZ Action Plan

There are currently 114 seabird species classified as vulnerable, endangered, critically endangered or critically endangered/ possibly extinct by the IUCN Red List (IUCN, 2020). Of these species, 99 are incorporated in the mPVA, with omissions due to extreme data deficiencies and species that breed on continents. The NZ Action Plan describes 46 species and subspecies, 27 of which we included in this study. We excluded species from this study that are not considered globally threatened, are not incorporated into the mPVA seabird database, or the NZ Action Plan only called for interventions outside of the scope of the seabird mPVA model scenarios (Supplemental Materials Table A.1). The 27 species included here consist of 337 confirmed and probable global breeding populations (Fig. 1), with New Zealand territories containing 48% of these populations across 105 islands (Supplemental Materials Table A.2).

For each focal species, we ran a suite of model simulations for the baseline (status quo) scenario, as well as alternative scenarios that corresponded to interventions dictated by the NZ Action Plan. We projected meta-population dynamics forward for 100 years, and replicated model runs 10,000 times to account for demographic and environmental stochasticity as well as parameter uncertainty (by drawing all seabird mPVA parameters from their respective posterior distributions). We associated each species with a quasi-extinction threshold (an a priori threshold below which the species was considered extremely likely to go extinct) of 50 breeding pairs. We note that recommended quasi-extinction thresholds for seabirds vary within the literature, and the value we used is a conservative threshold below which extinction risk due to natural disaster or genetic diversity loss is likely. For each scenario, we determined the mean expected metapopulation abundance after 100 years along with 95% confidence intervals, and the mean proportion of simulations with population sizes that fell below the quasi extinction threshold at 100 years to yield mean projected quasi-extinction risk, but rather an index of relative vulnerability that can be used to compare conservation gains across alternative scenarios. The NZ Action classifies proposed interventions by priority rank: Essential Actions, High Actions, Medium Actions, and Low Actions. Priority ranks set in the NZ Action Plan are intended to denote urgency. Each priority rank scenario was first simulated independently. Then we simulated





all prescribed interventions concurrently, under the "All" scenario. In total, this consisted of 83 scenarios (Supplemental Table A.3). Here we focus on Baseline and All intervention scenarios.

The interventions proposed in the NZ Action Plan were often regionally specific, however the model generated the global trajectory of the seabird species. Proposed actions included detailed measures, such as removing particular invasive predators from certain islands and translocations or reintroductions at specific sites. In these cases, we included as much detail described in the NZ Action Plan as possible in the scenario. In the case of translocations, we incorporated prescribed breeding site data (island size and location) whenever possible. When translocation was prescribed without a target site, we set the translocation site location as the midpoint between the two largest breeding colonies with a standardized size of 2 km². The number of individuals to be translocated was not specified in the NZ Action Plan. Therefore, we standardized the size of translocation populations to 400 juveniles to present an optimum scenario based on a review of published seabird translocation population sizes documenting 130 attempted seabird colony movements with an average of 373 individuals translocated (Jones and Kress, 2012; Miskelly et al., 2009; Lincoln Park Zoo, 2010) (Supplemental Materials Table A.4).

In the case of less detailed proposed actions, we made certain assumptions to apply standardized treatments. Thus, when the NZ Action Plan called for a reduction in bycatch, we adjusted at-sea mortality by the mean estimated total annual potential fatalities (APF) due to trawl, longline, and set-net fisheries within New Zealand territories (MPI, 2019). APF was reported as individuals without age class information. However, at-sea mortality adjustments are modeled to affect age classes in proportion to their abundance within the seabird mPVA. As the NZ Action Plan called for measures to improve survival at specific life stages, such as construction of wind shields to increase hatching success. In the absence of specific vital rate targets, we modeled "high" and "low" scenarios simulating 20% or 10% improvements to the vital rate of interest (Supplemental Materials Table 3).

2.3. Statistical analysis

To determine the credible difference of viability gains under management scenarios relative to baseline scenarios, we used a Bayesian model comparison approach. We examined the posterior predictive distribution of the difference of means projected under baseline and treatment scenarios and assessed whether the null value (0, indicating no difference) fell within credible parameter values (95% CI). Therefore, rejection of the null value indicated the difference of means was credible and statistically significant.

3. Results

3.1. Baseline quasi-extinction risk and current threat statuses

Baseline (current) mean projected quasi-extinction risk and uncertainty varied considerably among the 27 species (Fig. 2). Over a quarter (26%) of species scored a baseline mean projected quasi-extinction risk > 0.80 with reasonable certainty. Some species, notably the Pitt Island Shag and Black-fronted Tern, demonstrated high uncertainty in baseline mean projected quasiextinction risk, indicating poor parameter confidence. Nearly half (48%) of species were projected to have a baseline mean quasi-extinction risk of 0 with high certainty.

When species were ranked by baseline mean projected quasi-extinction risk and evaluated against current Red List status, we identified several inconsistencies, especially for species with the highest mean projected quasi-extinction risk (Table 1). Of the seven species with a baseline mean projected quasi-extinction risk > 0.80, four species (Fairy Tern, Stewart Island Shag, Rough-faced Shag, Auckland Island Shag) are listed as vulnerable, the lowest category of threat included in this study. Similarly, the Red List categorizes the Magenta Petrel as critically endangered, however we estimated a relatively low baseline mean quasi-extinction risk (0.01, 0–0.05 95% CI). Three species (Grey-headed Albatross, Hutton's Shearwater, Westland Petrel) are categorized as endangered, while we predicted relatively low baseline mean projected quasi-extinction risk. The remaining 10 species with a baseline mean projected quasi-extinction risk of 0 are classified as vulnerable.

Of the seven species with the baseline mean projected quasi-extinction risk > 0.80, the New Zealand Threat Classification System (NZTCS) assessed six species as threatened (nationally critical n = 3, nationally endangered n = 2, or nationally vulnerable n = 1). Meanwhile, the Stewart Island Shag, with a high baseline mean projected quasi-extinction risk (0.97, 0.91–1.00 95% Cl), is considered to be at risk-recovering (NZTCS).

3.2. Changes in viability under intervention scenarios

We simulated 83 conservation action scenarios. One third of these scenarios represented baseline (no intervention) conditions averaging a mean projected quasi-extinction risk of 0.32 spanning all possible outcomes (0–1). When considering the difference between baseline and prescribed intervention scenarios, there was little compelling evidence that significant conservation gains were associated with the priority assigned to scenarios (Fig. 3). Within species, there was congruence between decrease in mean projected quasi-extinction risk, regardless of credible difference, and the hierarchical order of priority assigned to interventions scenarios in 52% of instances. For mean final abundance, population trends tracked scenario priorities 84% of the time (Supplemental Materials Table A.5).



Fig. 2. Baseline mean projected quasi-extinction risks, 95% confidence intervals, and IUCN Red List status for 27 threatened New Zealand seabird species.

Next, we excluded delineations between scenario priorities and instead present only the results for baseline (no intervention) and all (comprehensive intervention) scenarios for each species as this captures maximum potential viability gains. Only nine species (Antipodean Albatross, Auckland Island Shag, Black-fronted Tern, Fairy Tern, Rough-faced Shag, Northern Royal Albatross, Pitt Island Shag, Stewart Island Shag, Yellow-eyed Penguin) saw mean credible (95% certainty) reductions in projected quasi-extinction risk when all prescribed interventions were simulated. For these nine species, mean credible decreases in projected quasi-extinction risk ranged from 0.04 to 0.76 (Table 2). The highest ameliorations in risk were 0.76 and 0.23 for Black-fronted Tern and Fairy Tern, respectively.

Difference of means in log transformed estimated abundance increases under all scenarios relative to baseline scenarios ranged from 0.02 to 5.16. Ten species were projected to more than double in abundance in the all scenario relative to baseline scenario (Black-fronted Tern, Fairy Tern, Stewart Island Shag, Northern Royal Albatross, Black Petrel, Antipodean Albatross, Snare's Crested Penguin, Rough-faced Shag, Chatham Island Shag, Auckland Island Shag) with 95% confidence (Supplemental Materials Table A.6).

We examined proposed intervention actions for trends between frequency of prescription and viability change. For the all intervention actions, we calculated the weighted average of credible viability gains (relative to baseline scenarios) across all species (Supplemental Materials Table A.7). Invasive species removal was prescribed with the highest frequency (24 scenarios, eight credible decreases in quasi-extinction risk) but ranked second for the greatest weighted-average decrease in mean projected quasi-extinction risk (6%) with credible log transformed increases in abundances ranging from – 0.04–3. The second most frequently prescribed action was translocation, which was simulated in 20 scenarios (six credible decreases in quasi-extinction risk) and was ranked third in weighted average decrease in mean projected quasi-extinction risk (5%) with credible log transformed increases in abundances ranging from – 0.06–1.49. Interventions that were intended to provide direct improvements to a specific vital rate (such as the construction of wind shields to increase hatching success) were prescribed nine times (eight credible decreases in quasi-extinction risk) but yielded the highest viability gains in mean projected quasi-extinction risk (32%) with credible log transformed increases in abundances ranging from -0.03 to 5.16. Bycatch mitigation was

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Species threat status, mean projected quasi-extinction risk, final mean abundance, and associated intervention scenario.

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Common Name	Threat Status IUCN /NZTCS	Initial Modeled Abundance	IUCN Population Trajectory	Scenario	Mean Projected Quasi- extinction risk	Mean Projected Quasi- extinction Risk 95% CI	Mean Final Abundance	Mean Final Abundance 95% CI
Chatham Is. Shag	Critically Endangered Threatened-Nationally Critical	904	Decreasing	Baseline All	1 0.99	0.99–1 0.98–1	1 2	0 - 4 0 - 10
Fairy Tern	Vulnerable Threatened-Nationally Critical ^a	8250	Decreasing	Baseline All	0.98 0.82	0.94–1 0.68–0.91	6 185	0 - 34 44 - 519
Stewart Is. Shag	Vulnerable At Risk-Recovering	5428	Decreasing	Baseline All	0.97 0.9	0.9–1 0.79–0.96	10 56	1 - 57 11 - 177
Antipodean Albatross	Endangered Threatened-Nationally Critical	87086	Decreasing	Baseline All	0.95 0.91	0.91-0.98 0.87-0.94	13 37	4 - 32 17 - 68
Rough-faced Shag	Vulnerable Threatened-Nationally Endangered	802	Stable	Baseline All	0.93 0.85	0.81-0.98 0.7-0.94	30 67	6 – 91 21 – 160
Auckland Is. Shag	Vulnerable Threatened-Nationally Vulnerable	3812	Stable	Baseline All	0.92 0.85	0.76-0.98 0.68-0.95	38 81	4 - 167 14-270
Yellow-eyed Penguin	Endangered Threatened-Nationally Endangered	6874	Decreasing	Baseline All	0.82 0.78	0.72-0.9 0.69-0.86	139 225	50 - 303 97 - 439
Black-fronted Tern	Endangered Threatened-Nationally Endangered	8162	Decreasing	Baseline All	0.63 0.01	0.07-0.98 0-0.05	51 6389	3 – 327 3792 – 9984
Pitt Is. Shag	Endangered Threatened-Nationally Critical	1094	Decreasing	Baseline All	0.6 0.48	0.3-0.85 0.24-0.73	183 294	56 - 441 126 - 575
Northern Royal Albatross	Endangered At Risk-Naturally Uncommon	30080	Decreasing	Baseline All	0.51 0.3	0.37-0.66 0.19-0.43	534 1936	224 - 1062 939 - 3492
Fiorland Crested Penguin	Vulnerable Threatened-Nationally Vulnerable	9520	Decreasing	Baseline All	0.18 0.2	0.04-0.44 0.07-0.42	2375 2957	936 - 4910 1267 - 5793
Chatham Albatross	Vulnerable At Risk-Naturally Uncommon	17652	Stable	Baseline All	0.17 0.17	0.08-0.31 0.09-0.28	1513 2058	770–2641 1102 – 3464
Snares Crested Penguin	Vulnerable At Risk-Naturally Uncommon	96912	Stable	Baseline All	0.01	0-0.08 0-0.05	18006 40073	9020 - 31761 23719 - 62758
Magenta Petrel	Critically Endangered Threatened-Nationally Critical	136	Increasing	Baseline All	0.01	0-0.05 0-0.04	305 371	161 – 519 201 – 620
Black Petrel	Vulnerable Threatened-Nationally Vulnerable	8052	Stable	Baseline All	0	0-0.03 0-0	2163 5746	1561 –2903 5003 – 6560
Buller's Shearwater	Vulnerable At Risk-Naturally Uncommon	2500000	Stable	Baseline All	0	0-0	544989 611759	298842 – 902228 341066 – 1000775
Campbell	Vulnerable	68434	Increasing	Baseline	0	0-0	81858	63504 - 103461 (continued on next page)

Table 1 (continued)								
Common Name	Threat Status IUCN /NZTCS	Initial Modeled Abundance	IUCN Population Trajectory	Scenario	Mean Projected Quasi- extinction risk	Mean Projected Quasi- extinction Risk 95% CI	Mean Final Abundance	Mean Final Abundance 95% CI
Albatross	Threatened-Nationally Vulnerable			IIA	0	0-0	84721	67299 - 104929
Chatham Petrel	Vulnerable	1614	Increasing	Baseline	0	0-0	1964	1580 - 2407
	Threatened-Nationally Vulnerable			AII	0	0-0	2219	1691 – 2847
Cook's Petrel	Vulnerable	972388	Increasing	Baseline	0	0-0	868105	661240-1114388
	At Risk-Relict			AII	0	0-0	900751	691315- 1148930
Grey-headed	Endangered	390756	Decreasing	Baseline	0	0-0	272031	189185-376325
Albatross	Threatened-Nationally Vulnerable			AII	0	0-0	278014	196559 - 379534
Hutton's	Endangered	325002	Stable	Baseline	0	0-0	130081	80832 - 196431
Shearwater	Threatened-Nationally Vulnerable			All	0	0-0	149758	91864 - 228358
Pycroft's Petrel	Vulnerable	24834	Increasing	Baseline	0	0-0	20874	14187 – 29409
	At Risk-Recovering			All	0	0-0	21280	14670 - 29645
Salvin's Albatross	Vulnerable	128728	Unknown	Baseline	0	0-0	99629	63218 - 148075
	Threatened-Nationally Critical			All	0	0-0	176702	139623 - 219853
Southern Royal	Vulnerable	46676	Stable	Baseline	0	0-0.01	17360	11242 - 25402
Albatross	At Risk-Naturally Uncommon			AII	0	0-0.02	18739	12568 - 26682
Westland Petrel	Endangered	16132	Unknown	Baseline	0	0-0	10171	7012 - 14171
	At Risk-Naturally Uncommon			AII	0	0-0	15602	12047 - 19799
White-chinned	Vulnerable	4396776	Decreasing	Baseline	0	0-0	439490	204017 - 816423
Petrel	Not Threatened			AII	0	0-0	527908	261130 - 939283
White-necked	Vulnerable	143886	Increasing	Baseline	0	0-0	124631	92546 - 163434
Petrel	At Risk-Relict			All	0	0-0	135699	99641 - 179609

^a Refers to subspecies. New Zealand Threat Classification System 6.5.0. IUCN Red List 7 Birdlife 2020.

Fig. 3. Decrease in mean projected quasi-extinction risk by intervention scenario priority (Baseline - Prescribed Scenario).

recommended in 13 scenarios (four credible decreases in quasi-extinction risk) and yielded 4% decrease in projected quasiextinction risk with credible log transformed increases in abundances ranging from 0.02 to 1.01.

4. Discussion

Under no-intervention (baseline) scenarios, the seabird mPVA projected seven of the 27 species to have relatively high mean projected quasi-extinction risk (> 0.80) and 13 species to have relatively low mean projected quasi-extinction risk (0). The IUCN

Table 2

Mean credible (95% certainty) decrease in projected quasi-extinction risk and proportional increase in mean final abundances under all (comprehensive intervention) scenarios relative to baseline (no intervention).

Common name	Mean credible decrease in p 95% Cl	ojected quasi-extinction risk and	Proportional increase in abundance and 95% CI	
Black-fronted Tern	0.76	(0.75-0.76)	173.76	(115.27-261.94)
Northern Royal Albatross	0.23	(0.22-0.24)	3.76	(3.57-3.96)
Fairy Tern	0.15	(0.12-0.19)	20.07	(16.57-24.31)
Pitt Island Shag	0.14	(0.1-0.18)	1.59	(1.45-1.76)
Rough-faced Shag	0.07	(0.06-0.09)	2.2	(2.03-2.39)
Stewart Island Shag	0.07	(0.05-0.09)	4.43	(3.89-5.05)
Auckland Island Shag	0.06	(0.05-0.08)	2.04	(1.88-2.21)
Antipodean Albatross	0.04	(0.03-0.05)	2.46	(2.32-2.62)
Yellow-eyed Penguin	0.04	(0.03-0.06)	1.62	(1.54-1.71)

Red List conservation status of the species with high mean projected quasi-extinction risk was variable, with four species considered vulnerable, the lowest threat category in this study. Meanwhile, the New Zealand Threat Classification System (NZTCS) ranked these species largely as highly threatened. Species with low (0) mean projected quasi-extinction risk generally tracked Red List assessments with 77% considered vulnerable and only one species (Salvin's Albatross) considered threatened-nationally critical by the NZTCS. The mismatches between mean projected quasi-extinction risk and assessments by the Red List or NZTCS are likely attributed to the different approaches underlying these evaluations. While the seabird mPVA relies on a consistent quantitative analysis to determine mean projected quasi-extinction risk for all species, the Red List and NZTCS rely on various quantitative and qualitative criteria to assess extinction risk. Additionally, the seabird mPVA applies a single timeframe to all species while the Red List and NZTCS vary timeframe by risk criteria and generation length. Therefore, discordance between the seabird mPVA results and current national and international assessments represent different methods in risk evaluation rather than inaccuracies. Despite these caveats, these findings suggest that closer examination, beyond global and national threatened species lists, is required to ensure that resources are properly apportioned within threatened taxa.

When comparing viability measures between baseline and all prescribed actions scenarios (Table A.7), the seabird mPVA projected mean credible decreases in projected quasi-extinction risk for nine species, with the Black-fronted Tern and Fairy Tern presenting the greatest differences between baseline and all scenarios (0.76 and 0.23, respectively). The greatest credible log transformed increases in abundances were seen in the Black-fronted Tern (5.16), Fairy Tern (3), and Stewart Island Shag (1.54). Considering that all prescribed interventions involved modeling 67 conservation actions across 27 species, our results suggest that alternative actions might also be worth considering to reduce extinction risk for most of the focal species. To meet conservation goals, scenarios should be simulated to estimate the relative effect of novel combinations of actions, various reasonable targets for trialed actions (e.g. increasing translocation sites, increasing bycatch mitigation), and coordinated actions executed beyond national borders.

Beyond examining baseline and comprehensive interventions, we also considered how the priority assigned to conservation plans related to viability gains. The NZ Action Plan based intervention priority on perceived urgency. We found limited correlations between intervention priority and modeled gains in mean projected quasi-extinction risk or mean final abundance. We found trends in viability gains (without regard for credible differences between measures) tracked scenario priority in 84% and 52% of cases for mean final abundance and mean projected quasi-extinction risk, respectively. One limitation to this analysis was the uneven distribution of priority counts, ranging from 3 to 17. The divergence between prescribed scenario priority and modeled viability gains may be attributed to the 20-year gap between the NZ Action Plan publication (2000) and when the seabird mPVA simulates interventions (year 1, i.e. present-day). It is probable that seabird populations, threats, and our understanding of intervention efficacy have changed significantly during this interval. Nevertheless, the discrepancy between modeled viability gains and presumed consequence of prescribed actions raises the importance of testing assumptions prior to implementation. These results indicate that there may be a relationship between perceived urgency of prescribed actions and viability gains; however, it may not be equal between viability metrics and further research is needed to confirm this.

We further examined the relationship between prescribed actions and conservation gains. Effectiveness of conservation actions varied between viability measures (Table A.7). Interventions that involved direct manipulation of vital rates to model actions such as artificially incubating eggs intended to increase fledging success, had the greatest weighted-mean credible reduction on projected quasi-extinction risk (32%) and greatest log transformed increase in abundance (mean 5.16, Black-fronted Tern) while being prescribed with moderate frequency (nine scenarios). Actions that were recommended with the highest frequency, invasive species removal and translocation appeared to have less promise for conservation gain. While these two actions were recommended most often, they had limited impact on viability measures. These results suggest that conservation actions affect species in nuanced and unexpected ways, and reinforces the potential benefits of modeling the projected impact of actions before implementation.

An advantage to using the seabird mPVA to predict quasi-extinction risk under various scenarios is the transparent reporting of uncertainty across all species and viability measures (quasi-extinction risk and increase in abundance). Notably, the Pitt Island Shag and the Black-fronted Tern were predicted to have high uncertainty in baseline mean projected quasi-extinction risk. There are several possible explanations for these results that merit further investigation before a recovery plan for these species is implemented. Uncertainty in parameter values and low starting populations are likely to account for the high uncertainty demonstrated by these two species. The Pitt Island Shag has a relatively low initial population size, which could lead to more uncertainty in population trajectories due to stochasticity. The Black-fronted Tern also has fairly low initial population size and is a single island endemic, but other species with similar initial population sizes or limited ranges demonstrated high confidence in viability predictions. This may be because similar species were projected with high certainty to either fall below quasi-extinction thresholds or steadily increase in abundance due to either unfavorable or advantageous vital rates and current population trends. Indeed, the 13 species with a mean projected quasi-extinction risk of 0, had the narrowest confidence intervals. These results are critical to pinpoint knowledge gaps and emphasize which species require further research before reliably making recovery plan predictions. In particular, dispersal rates data and adult and subadult survival rates should be improved. The seabird mPVA is designed to quickly incorporate improved data for future reevaluation of viability.

This study does not aim to be a precise predication of seabird populations into time. For one, the model does not approximate every ecosystem interaction, for instance interspecies competition for nesting sites or the effects of climate change on food availability. Nor does the model incorporate the feasibility, costs, and competing interests of stakeholders relevant to any of these interventions. Rather, this should be considered a first-round decision-making framework that provides a

systematic analysis across species to assess the potential conservation gains of suites of actions. A key benefit to this approach is estimating the relative benefit of conservation scenarios. The caveats bounding the results of this study are not unique and should be considered alongside other guidance on appropriate applications of PVAs (Morris et al., 1999; Brook et al., 2000; Coulson et al., 2001).

The framework we present here provides a means to quickly and consistently project relative quasi-extinction risk across a highly threatened taxon. With our approach we are also able to evaluate conservation gains across a hierarchal national strategic plan before implementation. Performing these assessments before enactment provides the opportunity to consider which species and actions should be prioritized to more efficiently allocate limited conservation resources. This is timely given a recent assessment that endemic New Zealand birds extinction risk trends are higher today than 40 years ago (Garcia-R and Di Marco, 2020).

Beyond relevance to seabirds, this study outlines how a standardized approach might be applied to assessing conservation options for large groups of threated species wherein data related to well-known species can be generalized for poorly studied species, such as cetaceans or turtles. This data-driven method uniformly evaluates recovery plans, returning relative viability metrics that managers can compare across and within species to match conservation goals. Thus, managers may find efficiencies in recovery plans and compare potential costs and gains. With limited time and resources available for conservation, there is a need to rapidly maximize resources and understand confidence in recovery plans. This mPVA approach could be replicated for other threatened taxa to guide conservation efforts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01644.

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