Influences on recovery of seabirds on islands where invasive predators have been eradicated, with a focus on Procellariiformes

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SUPPLEMENTARY MATERIAL 1 Island status

Descriptions of the ecological status of islands are adapted from Taylor (1989; Table S2); the islands in the study ranged from class I to class VII. The categories are broad and lack specific criteria for a comprehensive description of the ecological status, but they provide an overall guideline. We acknowledge that every island is influenced by a variety of biogeochemical and stochastic influences that affect the biological communities present, and thus classifying the islands into such broad categories may misrepresent their true ecological status.

TABLE S1 Class descriptions of the status of islands included in our study including introduced mammal and habitat modification status (adapted from Taylor, 1989).

Class Code	Class	Description
I	Near pristine natural environment	These islands have not had, or are not known to have had, introduced mammals present. The vegetation may have been modified by historical human activity but has recovered to or close to its pre-modified condition. The floral & faunal communities are likely to be representative of pristine island systems. Relict populations of rodent- or mammal-sensitive species are often present.
II	Outstanding quality natural environment	Introduced mammals are absent or have been removed. The vegetation has been modified through either land clearance (e.g. fires) or from the effects of introduced mammals. The flora & fauna are in mid-to-late stage recovery; forests are still in successional stages. Fauna are diverse & include rodent-sensitive species.
III	High quality natural environment	Introduced mammals are present or have recently been removed but are low-impact species. These islands have been highly modified by cultural harvesting/land-use but intact forest remnants remain. The floral & faunal communities are recovering, although they may be affected by the spread of invasive weeds & the continued disruption to seed dispersal or seedling recruitment if mammals are still present.
IV	Moderate quality natural environment	Introduced mammals are present & the islands have been extensively modified in the past. No intact forest remnants are present; however, the regeneration of successional stage forest is occurring (high potential for restoration).

V	Modified	Introduced mammals are either present or absent. The islands have been significantly modified by cultural or farming activities. The original vegetation is likely to have been completely cleared & the islands used as farmland. The current vegetation is grassland, patches of shrubland &/or tree ferns (high potential for restoration).
VI	Recreational	Introduced mammals are present & the island is at a high risk of continued reinvasion because of constant public use or permanent habitation. The islands are & continue to be extensively modified.
VII	Inshore	Introduced mammals are either present or not but the islands are within the swimming range of commensal rats, deer & stoats & are at high risk of invasion. Rodent-sensitive species may be present.

SUPPLEMENTARY MATERIAL 2 Data limitations

Some of the seabird data are out of date, and are biased towards heavily studied sites or sites that may not be representative of colony densities at locations that have not been sampled (Rayner et al., 2007). Furthermore, the number of records in the data set varied substantially between species, with some species represented by only a single data point. We did not account for occupancy during the breeding period; instead, we assumed that all of the presence records were of breeding colonies (or individuals). Sampling effort bias was not accounted for. Population census data were excluded from the statistical analysis. Estimating population size can be technically and practically challenging because many Procellariiformes nest in rugged, inaccessible locations and are nocturnal, and are therefore difficult to count directly (Rayner et al., 2007). Although these biases mean that making clear inferences from the data is challenging, the data set represents a relatively comprehensive picture of seabird presence and changes over time in response to predators and predator removals. Furthermore, as the data were collected by a small group of individuals over the time period of the data set, we believe the biases are likely to be consistent across the study area.

SUPPLEMENTARY MATERIAL 3 Taxonomic considerations

We grouped species and subspecies together: the New Zealand white-faced storm petrel *Pelagodroma marina maoriana* with the white-faced storm petrel *Pelagodroma marina*, and the North Island little shearwater *Puffinus assimilis haurakiensis* with the little shearwater *Puffinus assimilis*. Terns (family: Sternidae) and gulls (family: Laridae) were discarded from the analysis because they are confined to coastal areas and exhibit strong intraspecific aggression, and individual nest sites are often up to 1 km apart. Shags/cormorants (family: Phalacrocoracidae) were also discarded because they exhibit ephemeral breeding site selection behaviour (New Zealand Birds Online, 2015).

TABLE S2 Seabird species, IUCN Red List status, and mean age at first reproduction (AFR), from our review of seabird recovery on islands in the Hauraki Gulf, New Zealand (Fig. 1) following predator eradication.

Order	Scientific name	Common name	Description	AFR
Pelecaniformes	*Morus serrator*	Australasian gannet	Native IUCN status: Least Concern Population trend: increasing	5.5
Procellariiformes	*Procellaria parkinsoni*	Black (Parkinson's) petrel	Endemic IUCN status: Vulnerable Population trend: stable	6
Procellariiformes	*Pterodroma nigripennis*	Black-winged petrel	Native IUCN status: Least Concern Population trend: declining	3
Procellariiformes	*Ardenna bulleri*	Buller's shearwater	Endemic IUCN status: Vulnerable Population trend: stable	c. 5
Procellariiformes	*Pelecanoides urinatrix*	Common diving petrel	Native IUCN status: Least Concern Population trend: declining	2
Procellariiformes	*Pterodroma cookii*	Cook's petrel	Endemic IUCN status: Vulnerable Population trend: increasing	c. 3
Procellariiformes	*Pachyptila turtur*	Fairy prion	Native IUCN status: Least Concern Population trend: stable	3
Procellariiformes	*Ardenna carneipes*	Flesh-footed shearwater	Native IUCN status: Least Concern Population trend: declining	5
Procellariiformes	*Puffinus gavia*	Fluttering shearwater	Endemic IUCN status: Least Concern Population trend: relict	c. 5
Procellariiformes	*Pterodroma gouldi*	Grey-faced petrel	Endemic IUCN status: Least Concern Population trend: declining	5.5
Sphenisciformes	*Eudyptula minor*	Little penguin	Native IUCN status: Least Concern Population trend: declining	2.5
Procellariiformes	*Puffinus assimilis*	Little shearwater	Native IUCN status: Least Concern Population trend: declining	c. 4
Procellariiformes	*Fregetta maoriana*	New Zealand storm petrel	Endemic IUCN status: Critically Endangered Population trend: unknown	c. 2.5
Procellariiformes	*Pterodroma pycrofti*	Pycroft's petrel	Endemic IUCN status: Vulnerable Population trend: increasing	3
Procellariiformes	*Ardenna griseus*	Sooty shearwater	Native IUCN status: Near Threatened Population trend: declining	6
Procellariiformes	*Pelagodroma marina*	White-faced storm-petrel	Native IUCN status: Least Concern Population trend: declining	2.5

SUPPLEMENTARY MATERIAL 4 Additional Poisson GLM results

Results from the model selection show that model 3, with separate intercepts and slopes by predator status, has the lowest AICc (R Development Core Team, 2013; Table S3).

TABLE S3 Model selection results for the Poisson generalized linear model of the species–area relationship by predator status.

Predictors	df	AICc
log(area)	2	452.8
log(area) + Predator status	4	377.7
Predator status + log(area):Predator status	**6**	370.8

The Poisson generalized linear model assumes a linear mean–variance relationship (dispersion parameter =1). We checked this assumption using a dispersion test (*AER* package, Kleiber & Zeilis 2008, R Development Core Team, 2013). The dispersion parameter is estimated to be 0.99 and not significantly different from 1 ($z = -0.09$, $P = 0.53$). Hence, the assumption of a Poisson mean–variance relationship is met. Weak, but statistically significant spatial autocorrelation in the residuals was indicated by Moran's I ($I = 0.1$, $P = 0.01$), and visual inspection of spatial residuals indicated that this was attributable to the model over-predicting species richness for the islands of the inner Hauraki Gulf (Fig. S1).

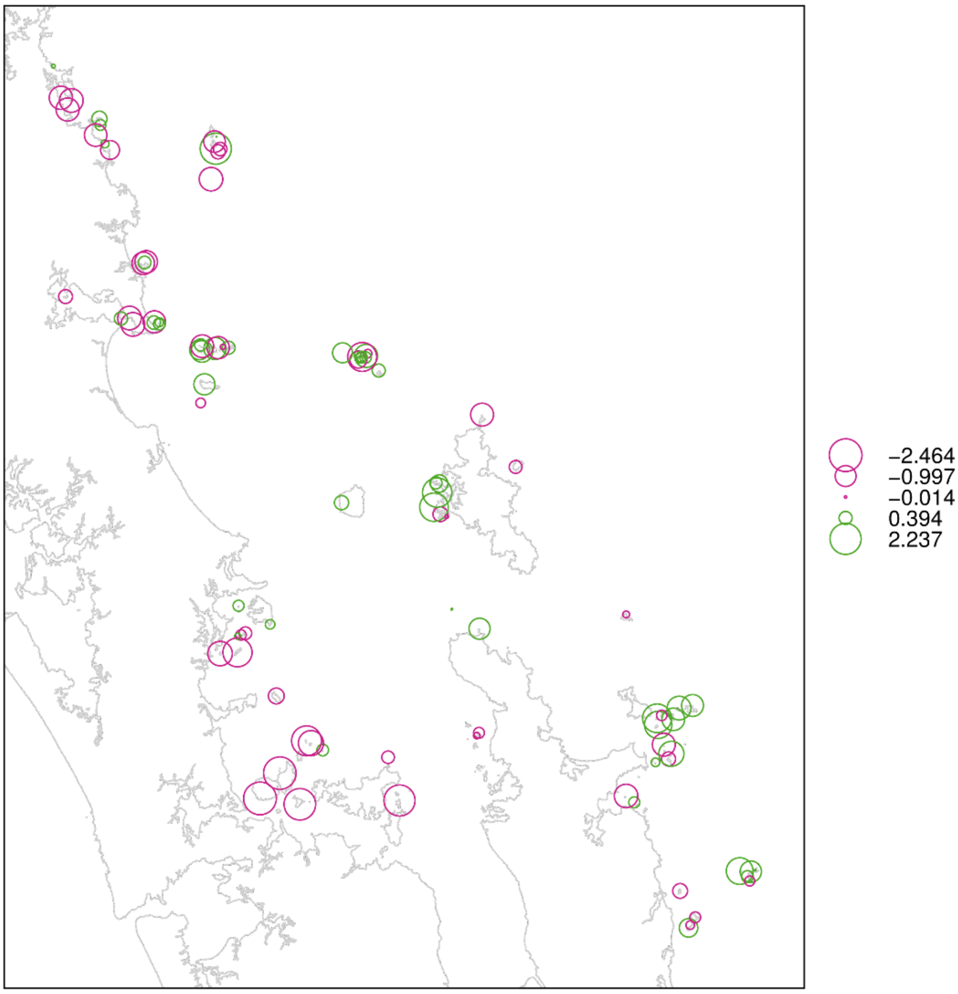

FIG. S1 Map of generalized linear model residuals for the species–area relationship by predator status.

Multi-model inference based on Poisson generalized linear models was used to explore possible predictors of species richness for the cleared islands (Burnham & Anderson, 2002). The predictors explored were size, time since eradication, distance to the mainland, and distance to Auckland, the latter two being potential proxies for human disturbance and/or distance to offshore feeding grounds. Distances were calculated using the rgeos package (Bivand & Rundel, 2016). We used the MuMIn package (Barton, 2015) to generate a complete set of candidate models based on the above predictors and ranked the resulting model fits by AICc. Multi-model inference did not provide strong evidence for a link between the time since eradication and species richness. Distance to Auckland emerged as a significant predictor in all six models that were within 3 AICc units of the optimal model, with higher species richness on islands further from the city. Distance to mainland and island size were each retained in three of the top six models and had a significant effect size only when they were not retained in the same model. Size had a positive effect on species richness, whereas distance to mainland had a negative effect (Table 3; Fig. S4).

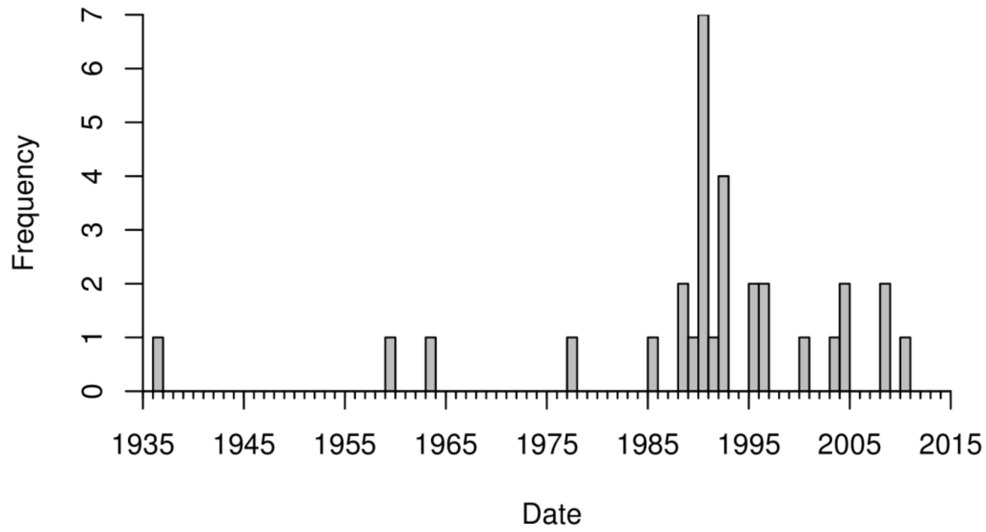

FIG. S2 Frequency distribution of eradications (n = 31) on islands in the Hauraki Gulf, New Zealand (Fig. 1) included in our study.

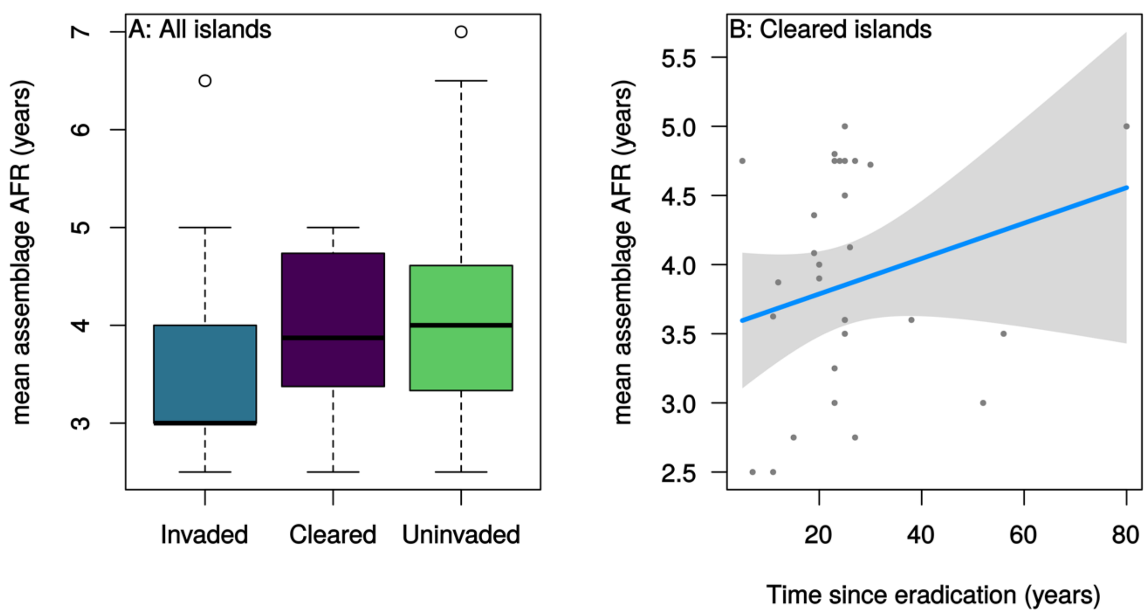

FIG. S3 (a) Mean age at first reproduction (averaged over all breeding species on a given island) by predator status. Differences are not statistically significant (Kruskal–Wallis rank sum test, χ^2 = 5.72, df = 2, P = 0.057). (b) Ordinary least squares regression of mean assemblage age at first reproduction against time since eradication for the cleared islands. The positive trend is not statistically significant ($\hat{\beta}$ = 0.013, P = 0.20).

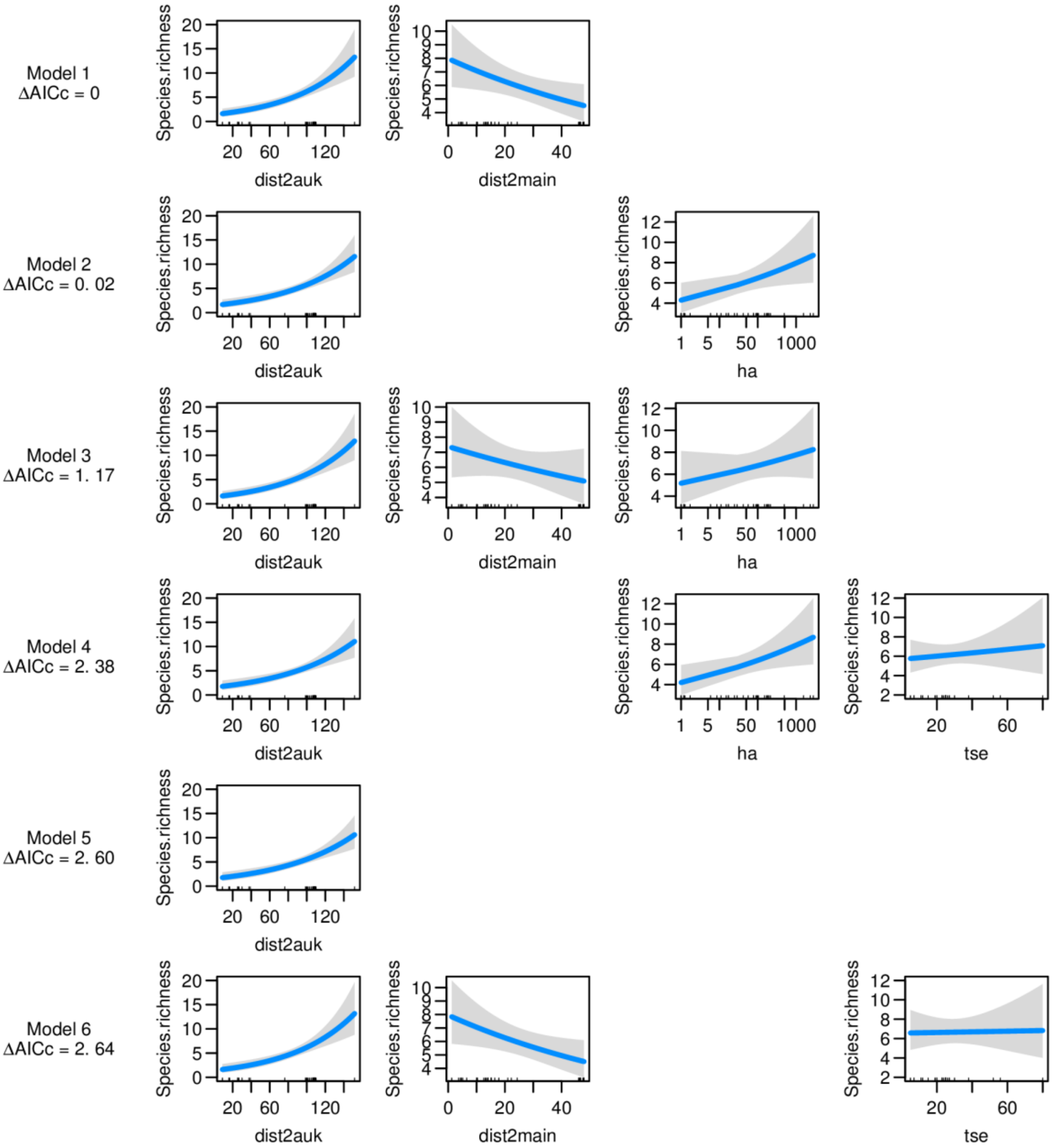

FIG. S4 Partial effect plots of the top six models of species richness on cleared islands from the multi-model selection procedure. Model parameter estimates and associated standard errors are in Table 3.