

Title: ENSO-driven rainfall pulse amplifies predation by owls on seabirds via apparent competition with mice

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Appendix S2. Supplemental methods and results for mathematical model

The relationships between murrelets, mice, and owls are described with a set of ordinary differential equations (ODE). The model is based on the Lotka-Volterra framework used for the classic hyperpredation model [1] and a similar model of apparent competition [2]. The models are then fit with empirical or derived parameters for our system (Table A1). For the mice (M) and owls (O), both are characterized by their intrinsic growth rate (r_i), carrying capacity (K_i), and mortality rates (μ_i). The mice are also subject to mortality from predation by owls (γ), relative to adult murrelets (S). Their populations then thus can be represented by:

$$\frac{dM}{dt} = r_m M \left(1 - \frac{M}{K_m}\right) - \mu_m M - \frac{M}{M + S} \gamma_m^o O \quad (\text{eqn. 1})$$

$$\frac{dO}{dt} = r_o O \left(1 - \frac{O}{K_o}\right) - \mu_o O \quad (\text{eqn. 2})$$

The carrying capacities of mice and owls are linked by their respective predation rates on their respective main prey (γ_i^i), which results in realistic population sizes for the island. The carrying capacity of mice and owls then varies over time through the action of the climate forcing variable (C).

$$K_m = \left(\frac{V}{\gamma_v^m}\right) C \quad (\text{eqn. 3})$$

$$K_o = \left(\frac{M}{\gamma_m^o} \right) C \quad (\text{eqn. 4})$$

We extracted monthly estimates of precipitation from the PRISM 4-km gridded surface and compiled them into rainfall year totals for the island during 1897-2015 (PRISM; [3]). This time series of estimated historical precipitation was then rescaled into a range of proportional values (minimum =0.03, maximum = 3.5) with the R package ‘scales’ to create the vector representing variable climate driven resources (C) that directly influences carrying capacities of mice and owls in the model.

Seabird adults (S) are represented by an intrinsic growth rate (r_s) and the number of breeding seabird adults (S), modified by a fixed carrying capacity (K_s). Adult murrelet population change is then subject to mortality from reasons other than predation (μ_s), as well as a predation rate of owls (O) on murrelets relative to mice as an alternative prey for owls (γ).

$$\frac{dS}{dt} = r_s S \left(1 - \frac{S}{K_s} \right) - \mu_s S - \frac{S}{M + S} \gamma_s^o S O \quad (\text{eqn. 5})$$

All analyses were done in R 3.2.1 (R Core Team, 2014). Differential equations were solved numerically with the function *ode* with the R package ‘deSolve’ [4]. Initial population sizes were set to: $S=1125$, $M=1600$, and $O=3$. Maximum intrinsic rates of growth (r_i) were estimated based on the Cole’s equation [5] $1 = e^{-r_{\max}} + b e^{-r_{\max}(a)} - b e^{-r_{\max}(w+1)}$ with empirical parameters for each species (b =fecundity, a =age of first breeding, and w =lifespan) following Sol et al. 2012 [6].

Parameter	Value	Reference(s)
Deer mouse growth rate (r)	12.4	Collins et al. 1979 [7]
Mouse predation on vegetation (γ)	0.05	fixed
Vegetation (V)	1000	fixed
Deer mouse mortality rate (μ)	0.22	Ozer et al. 2011 [8]
Owl predation on mice (γ)	2130	Thomsen and Plumb 2014 [9]
Barn owl growth rate (r)	2.2	this study; Taylor 2004 [10]
Barn owl mortality (μ)	0.25	Taylor 2004 [10]
Murrelet growth rate (r)	0.38	NPS unpub. data; Nur et al. 2013 [11]
Murrelet carrying capacity (K)	3500	fixed
Murrelet adult mortality (μ)	0.16	Nur et al. 2013 [11]
Owl predation on murrelets (γ)	0.18	this study (max proportional rate = 172/475 pairs)

Table A1. Summary of parameter values used in the model

The model was first run without climate forcing ($C=1$) to 120 time steps (years) to determine whether stable equilibrium values could be reached under constant conditions (Figure A1). The model converged at a stable equilibrium where none of the three species trended towards extinction nor exhibited any cyclic dynamics. This demonstrates that the population fluctuations in the model were due to external climate forcing and not endogenously generated limit cycles. We then ran the model with climate (C) set to vary as a function of the time series of rainfall (Figure A2, A3). We show that increasing bottom-up perturbations from rainfall can lead to subsequent declines in the population size of murrelets from predation by owls (Figure A4).

We also confirmed the robustness of the model results to parameter values by changing the parameters by $\pm 10\%$ following Roemer et al. [12] and verified that output values and dynamics remained similar. To assess the accuracy of the model output, we compared the

predicted values to observed population dynamics of mice and owls as well as predation on murrelets with correlation analyses and the mean absolute error (MAE)[13]. The predicted dynamics of the mouse population from the model are similar to those actually observed on the island based on an index of mouse abundance over 23 years (1992-2015; Figure A5; $r = 0.43$ $p=0.04$), particularly since the year 2001 ($r = 0.73$ $p=0.003$). The model also performs fairly well in predicting owl abundance similar to the observed variation on the island ($r = 0.64$ $p=0.03$; mean absolute error (MAE)= 5.5; $n=12$ years; mean annual abundance as estimated from trail surveys; data from this study, [14,15], NPS unpub data). The model also does a fair job at predicting the number of murrelets killed by owls ($r=0.72$; $p=0.03$; MAE= 56; $n=9$ years; data from this study; [14,16], see Figure 4 in main text).

Unfortunately, nocturnal crevice-nesting seabirds like Scripps's murrelets are notoriously difficult to monitor and develop precise estimates of population sizes [17,18], so we could not include that data to test our model. The range in estimated breeding population size is often quite wide and uncertain (475-650 breeding pairs; Whitworth, pers. comm.), meaning that those estimates are best suited for detecting long-term trends in population size on the island rather than detecting inter-annual fluctuations, which would be needed to test the model output.

There has been an ongoing trend of increasing variance in rainfall over the last few decades in California [19]. We also examined the annual precipitation data for trends over time based on rolling ten-year windows of the mean and standard deviation and then tested for a correlation between variance in climate and the variance in murrelet population changes in the model. There was an increasing trend in the variance of precipitation in rolling ten-year windows from 1897 to 2015 ($n=109$, $\rho=0.72$, $p<0.001$) but no corresponding change in the mean ($n=109$, $\rho=-0.11$, $p=0.24$). Similarly, there was an increasing trend in the variance of the ratio

of murrelet population changes predicted by the model ($n=109$, $\rho=0.51$, $p<0.001$), which was also correlated with changes in the variance in rainfall ($n=109$, $\rho=0.62$, $p<0.001$). Only 7.5% of observations were \geq the number of murrelets found killed in 2012 (172), and most (66%) of those instances occurred since 1980.

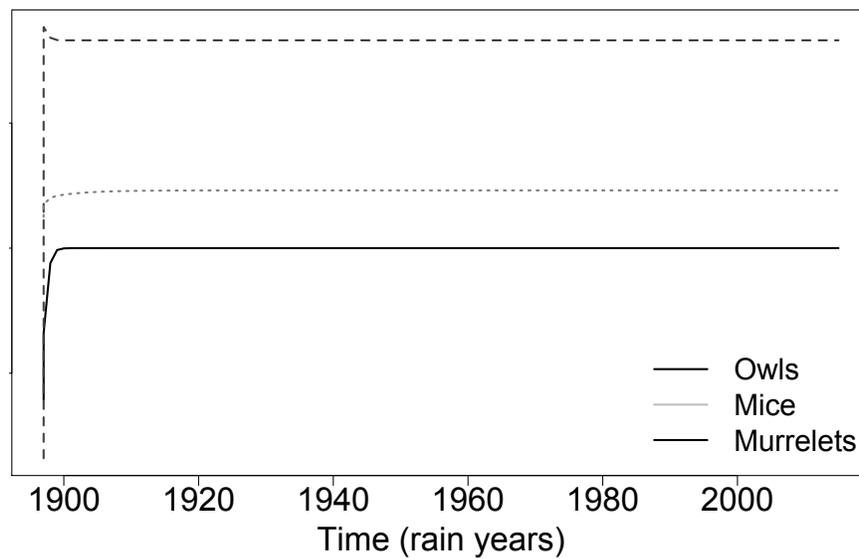


Figure A1. Simulated population dynamics with no climate forcing ($C=1$) over 120 years to demonstrate stable equilibrium is reached after a short transient period. Y-axis values in figure are arbitrary.

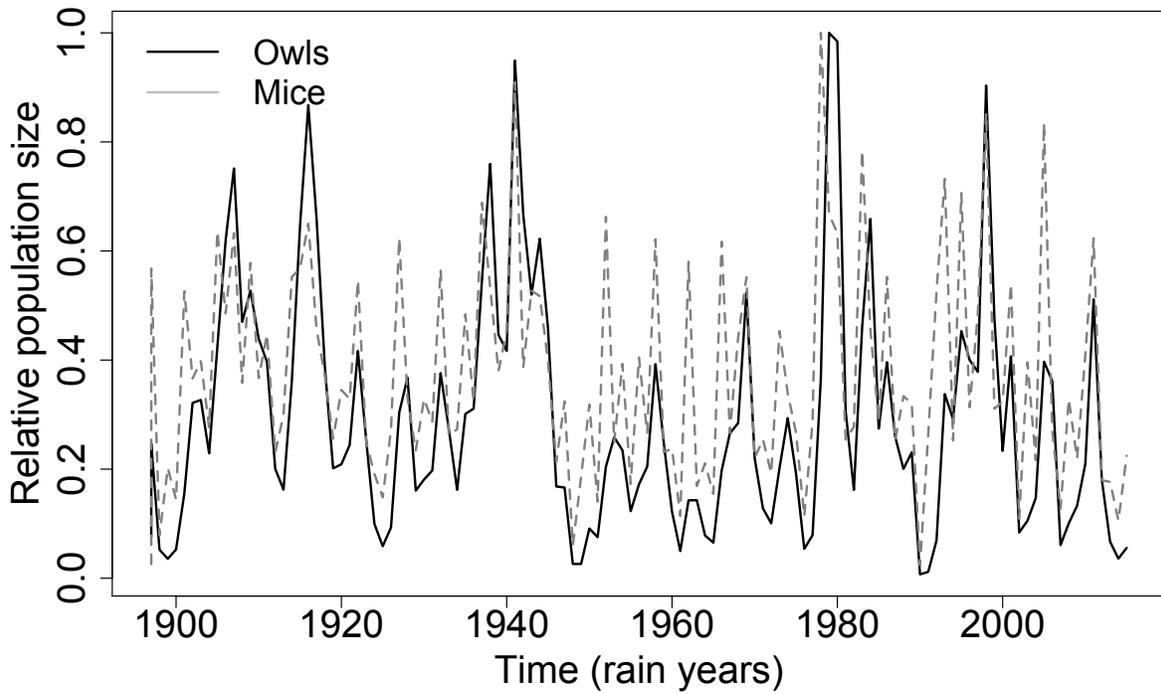


Figure A2. Model output showing population changes in mice and owls over 120 years based on estimated historical rainfall. Values were rescaled for this figure relative to their maximum abundances predicted by the model (peak abundance for mice = 61840; peak abundance for owls = 40).

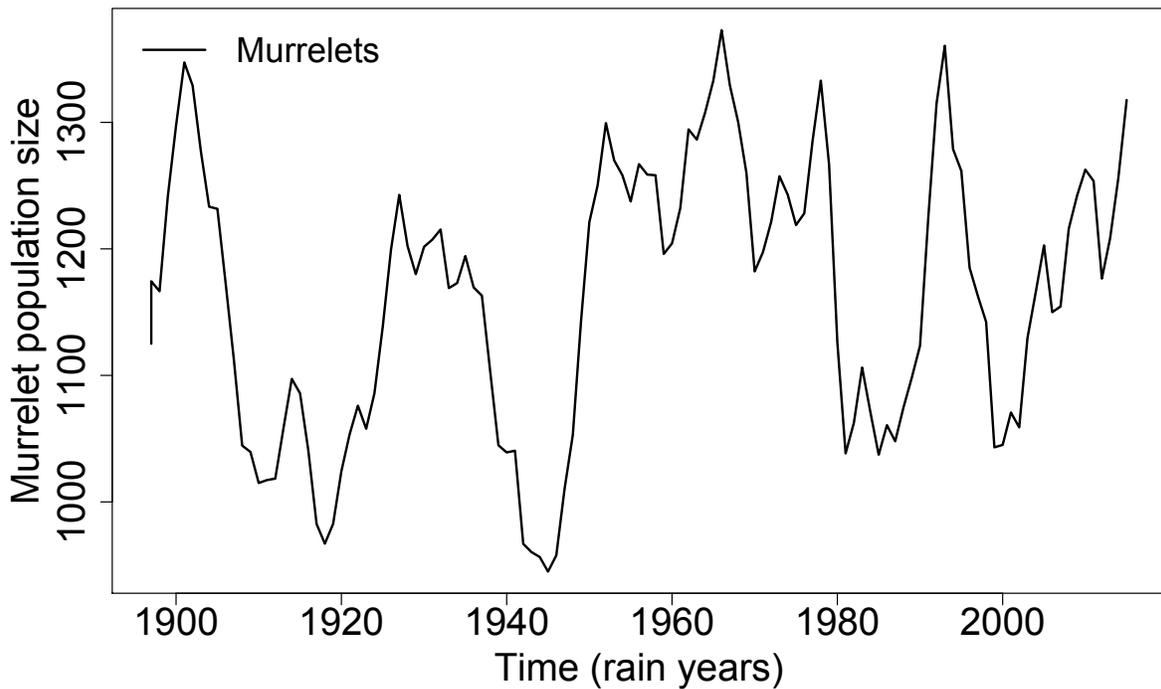


Figure A3. Simulated population changes in murrelets over 120 years

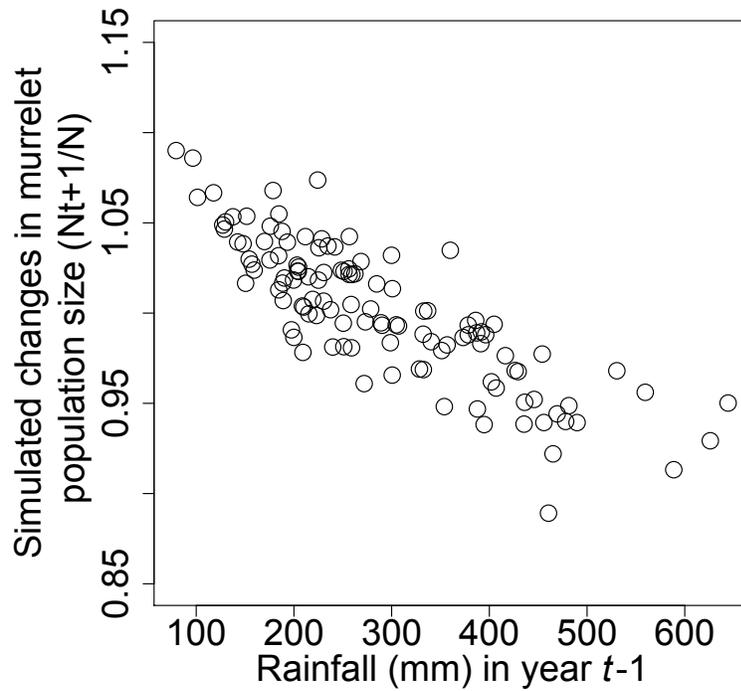


Figure A4. Annual changes in murrelet abundance (values <1 indicate declines) as predicted by rainfall from the year before in the simulation model

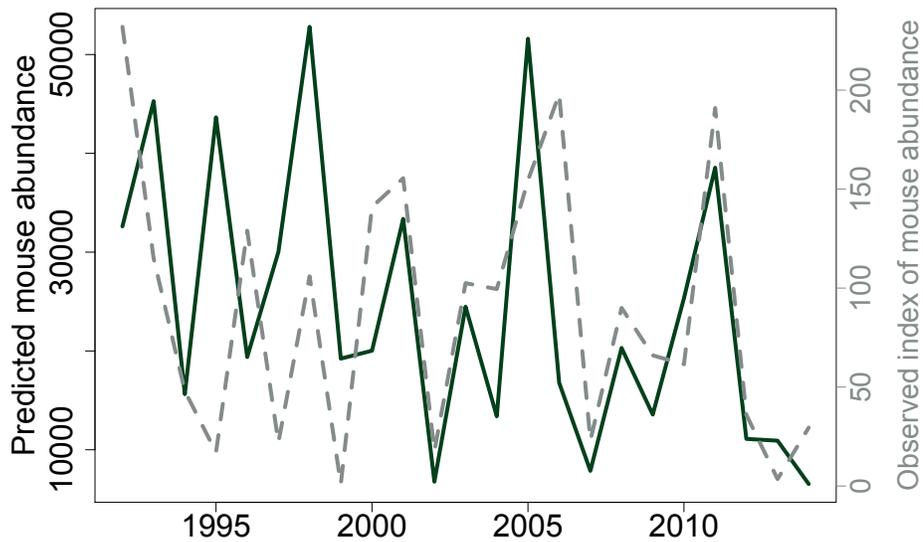


Figure A5. Predicted (solid line) and observed (dashed line) mouse abundance on Santa Barbara Island from 1992-2015. Observed index of mouse abundance (the number of unique individuals captured averaged by year in the Terrace Coreopsis plot) is from published NPS reports [20-22].

Positive precipitation anomalies for southern California are generally associated with ENSO events persisting into late winter (JFM/FMA; defined as the ‘Oceanic Niño Index’ ONI of 0.5 degrees C; [23]). Years with such events occurred in 1992, 1995, 1998, 2003, 2005, 2010, and 2015 based on data obtained from:

http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php.

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