# Supporting Information


## Maclean and Wilson 10.1073/pnas.1017352108


### SI Methods

**Using the International Union for Conservation of Nature (IUCN) Red List to Determine Extinction Risk from Rates of Population Decline.** The IUCN Red List criteria provided a means of assigning each taxon studied to a particular threat category on the basis of either extinction risk or observed or projected changes in population size over set time periods. Although the variation among species is such that it is not possible to fully validate the equivalence of the thresholds using different criteria (1), broad consistency among criteria was sought during the development of the IUCN Red List (2). It is, thus, reasonable to assume that a defined change in population size is broadly equivalent to a defined extinction probability. A taxon is critically endangered when the best available evidence indicates an observed, estimated, inferred, or suspected population size reduction of 80% over the last 10 y or three generations, whichever is longer, where the reduction or its causes may not have ceased, be understood, or be reversible. Alternatively, it is critically endangered when quantitative analysis shows that the probability of extinction in the wild is at least 50% within 10 y or three generations, whichever is longer. There are similar criteria for the other categories. A taxon is endangered if the population size reduction is 50% over 10 y or probability of extinction is 20% in 20 y, and a taxon is vulnerable if the population size reduction is 30% over 10 y or probability of extinction is 10% over 100 y.

Extinction risks can be standardized over any given period using multiple event probability theories (Eq. **S1**):

$$E_s = 1 - (1 - E_t)^{\frac{s}{t}}, \qquad \textbf{[S1]}$$

where $E_s$ is the extinction probability of the desired time period $s$ and $E_t$ is the extinction probability over time period $t$. When extinction probabilities associated with each of the three IUCN Red List categories are standardized to 55.628 y and logit transforms are applied to ensure a continuous range of values, there is a perfectly linear relationship with the equivalent population size reductions over 10 y in each of the IUCN Red List categories (Fig. S1). It is, thus, possible to infer extinction risk for any given reduction in population size over a 10-y period. To determine the population changes over 10 y ($P_{10}$) from changes ($P_t$) over the time period ($t$) associated with each of the studies, we assumed that rates of population change remained constant through time and thus, could be calculated as follows: $P_{10} = 1 - \exp(10r)$, where $r$ is the annual rate of change in population given by $r = \ln\left(\frac{1-P_t}{t}\right)$.

Because there are inherent problems associated with validating the equivalence of the thresholds in different criteria (1), we tested the sensitivity of our results to a range of assumed relationships between reduction in population size and probability of extinction; the analyses presented in Fig. S1 were repeated with slope values of 12 and 15 and intercept values of −5 and −8. The equivalent probabilities of extinction are given in Table S3. Even with very different extinction probability values assumed for each IUCN Red List category, our results are relatively robust, with expected extinction probabilities from climate change varying by considerably less than one order of magnitude (Table S3).

To further test the impact of the extent to which criteria and methodologies might yield dissimilar estimates of extinction risk, we assigned all of our responses to one of three methods: (*i*) observed or predicted range shifts, (*ii*) observed or predicted changes in population size, or (*iii*) direct estimates of extinction risk as determined by IUCN listing or population viability analysis. Direct predictions of extinction, determined by population viability analyses, yielded higher estimates of extinction risk than estimates provided by population decline and range size (Fig. S3). However, we suspect that this finding is primarily caused by such studies focusing on particularly endangered species rather than because of a lack of equivalency among IUCN criteria

**Climate Impact Types.** The potential effects of climate impact type on extinction estimates were assessed with a generalized linear model in R software (3) using comparisons of Akaike's Information Criterion (4) with the null model of extinction risk to assess whether, overall, impact type had an effect. Responses to five impact types were considered: (*i*) changes in ocean circulation patterns, such as intensification of El Niño, (*ii*) direct responses to changes in temperature and rainfall, (*iii*) indirect responses caused by changes in habitat, (*iv*) changes in sea ice coverage resulting from temperature or precipitation change, and (*v*) changes in ocean acidity resulting from increased levels of $CO_2$. Extinction risk was affected by impact type for both observed and predicted data; temperature and rainfall change significantly affected observed responses, and changes in ocean circulation patterns, habitat, and ocean acidification significantly affected predicted responses. The majority of studies reported threats from changes in temperature and rainfall, but studies on the effects of reductions in sea ice and changes in ocean circulation patterns showed higher estimates of extinction risk (Table S2).

**Screening for Publication Bias.** We compared the relationships between extinction risk and an estimate of the number of species included in each study (Fig. S2*A* and *B*) to assess whether there was a bias to studies on species that are particularly at risk of extinction. For studies in which ecological responses were reported for more than one taxonomic group, extinction risk estimates were averaged across taxa. For studies in which ecological responses have already been observed (Fig. S2*A*), there was no evidence of asymmetry, suggesting that no publication bias existed. For studies in which ecological responses were predicted (Fig. S2*B*), there is a slight tendency for studies in which more species were included to report higher extinction risks. This finding would imply a slight bias of studies on species that are at lower risk of extinction, suggesting that, overall, our estimates of extinction risk across species are conservative. We also compared the relationship between extinction risk and an estimate of the sample size per taxon of each study (Fig. S2 *C* and *D*). For both studies in which ecological responses have already been observed (Fig. S2*C*) and those studies in which responses were predicted (Fig. S2*D*), there is no evidence of asymmetry, suggesting that there was no publication bias to studies that report phenomena leading to particularly high extinction risks. The numbers in Fig. S2 refer to the study numbers listed in Table S2. One study of an observed response (5) and one study in which a prediction was made (6) reported responses equivalent to an extinction probability of very close to zero. They are, therefore, not included in Fig. S2, because the logit transform of zero is −∞. Another study (7) predicted a definite extinction and therefore, also could not be included in the plot.

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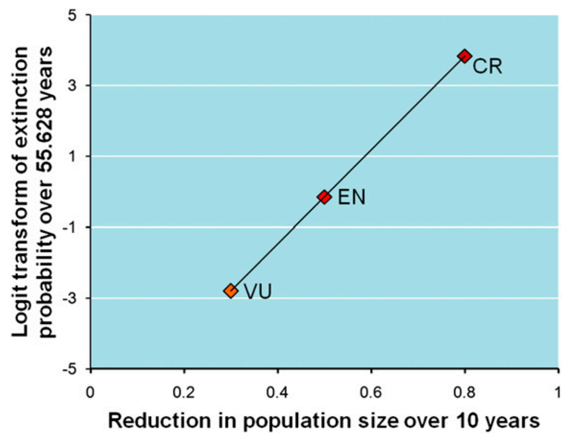


**Fig. S1.** Relationship between extinction probability and reduction in population size. Logit transform of extinction probability plotted against reduction in population size for each of the IUCN Red List categories. CR, critically endangered; EN, endangered; VU, vulnerable. The resulting relationship is perfectly linear, with a slope of 13.284 and an intercept of −6.793 (equivalent to an extinction probability of 0.00112).

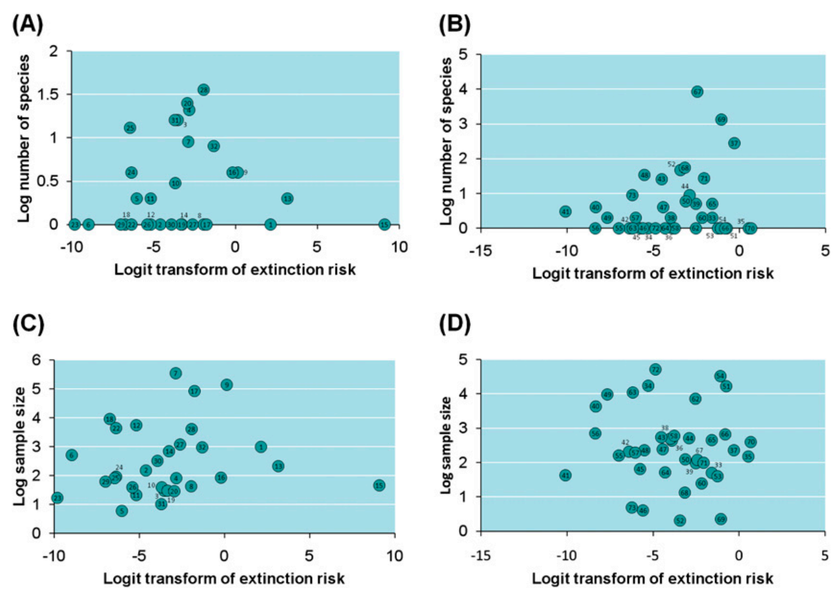


**Fig. S2.** Funnel plots to assess publication bias. Relationship between $\log_e$ of the estimated number of species in each study and the logit transform of extinction risk for (*A*) observed and (*B*) predicted responses. Relationships between $\log_e$ of the estimated sample size per taxon in each study and the logit transform of extinction risk for (*C*) observed and (*D*) predicted responses are also shown to screen for bias to research on particularly threatened species. The numbers refer to the studies listed in Table S3.

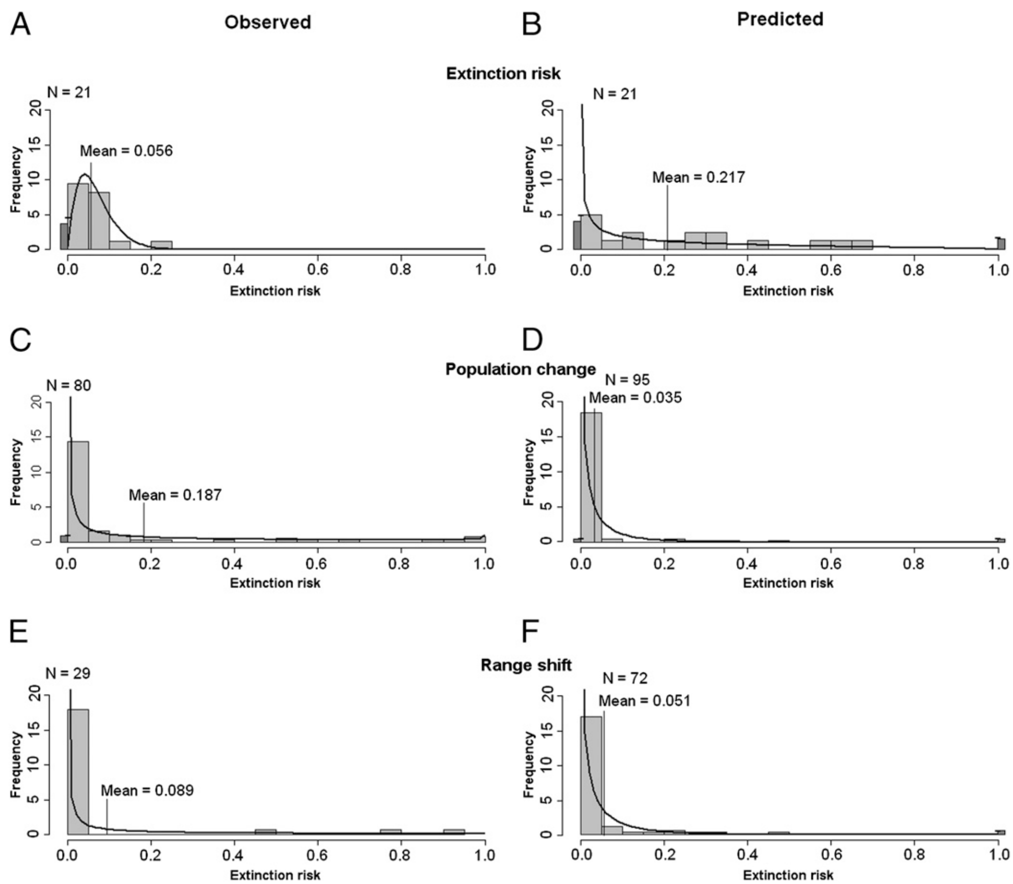


**Fig. S3.** Frequency distribution of extinction risk by 2100 as determined using different methodologies: (*A*) observed and (*B*) predicted estimates derived directly from IUCN listings or through population viability analysis, (*C*) observed and (*D*) predicted estimates derived from population changes, and (*E*) observed and (*F*) predicted estimates derived from range shifts. Actual proportion derived from studies (histogram bars) together with a fitted β-probability function (black curve). The dark bars (actual) and horizontal black lines (modeled) represent the frequency of studies with an extinction risk of zero or one. Data are scaled such that the total area of histogram bars and under the modeled extinction risk line is equal to one. *N* is the number of samples in each category.

**Table S1. Studies from which extinction risk estimates were extracted and the methods used to derive estimates**

| Study* | Method of estimating extinction risk |
|---|---|
| Barrett et al. (1) | Change in observed abundance |
| Both et al. (2) | Mean associated with changes in observed abundance across sites |
| Britton et al. (3) | Change in observed cover |
| Carpenter et al. (4) | IUCN risk category |
| Chen et al. (5) | Mean associated with changes in observed abundance across sites |
| Davies et al. (6) | Change in observed range |
| Field et al. (7) | Change in observed abundance since 1900 |
| Graham et al. (8) | Mean associated with changes in observed abundance across sites and functional groups |
| Hornfeldt et al. (9) | Estimated linear trend of observed population change |
| Jenouvrier et al. (10) | Estimated linear trend of observed population change |
| Kausrud et al. (11) | Estimated linear trend of observed population change |
| Kausrud et al. (12) | Estimated log-linear trend of observed population change |
| Lovvorn et al. (13) | Mean associated with changes in observed density at sampling points and observed change in area with suitably high prey densities |
| Ludwig et al. (14) | Mean associated with observed changes across sites |
| McEachern et al. (15) | Mean associated with linear trends of observed post-2003 abundance across sites |
| McMenamin et al. (16) | Change in observed number of populations |
| Montes–Hugo et al. (17) | Change in observed chlorophyll-a concentrations |
| Mueter and Litzow (18) | Change in observed catch per unit effort |
| Murphy et al. (19) | Estimated linear trend of observed population change |
| Pauli et al. (20) | Change in observed number of plots occupied |
| Pfeifer et al. (21) | Estimated linear trend of observed population change |
| Rolland et al. (22) | Estimated linear trend of observed population change |
| Rolland et al. (23) | Estimated linear trend of observed population change |
| Ruhl et al. (24) | Estimated linear trend of observed change in density |
| Smol et al. (25) | Mean associated with estimated linear regressions of observed population change across sites |
| Vargas et al. (26) | Estimated from observed change in sea-surface temperature (SST) and observed relationship between SST and change in numbers |
| Waite and Strickland (27) | Estimated linear trend of observed change in population as estimated by territory occupancy |
| Wallisdevries and Van Swaay (28) | Mean associated with observed changes in population across species |
| Walther et al. (29) | Observed change in range |
| Weatherhead (30) | Estimated linear trend of observed mean harem size |
| Wilson et al. (31) | Mean associated with observed range changes across species |
| Winder et al. (32) | Estimated linear trend of observed change in density |
| Anderson et al. (33) | Estimated linear trend of predicted change in population |
| Attorre et al. (34) | Predicted change in range from A1F1 Intergovernmental Panel on Climate Change (IPCC) Scenario |
| Baskett et al. (35) | Proportion of presented scenarios predicting extinction |
| Berkelmans and van Oppen (36) | Predicted change in density; time period estimated from IPCC scenarios and mean extinction risk across scenarios used |
| Bomhard et al. (37) | Mean IUCN risk category across species |
| Carroll (38) | Mean associated with predicted changes in population across presented scenarios |
| Chown et al. (39) | Predicted proportional change in density; time period estimated from IPCC scenarios and mean extinction risk across scenarios used |
| Colwell et al. (40) | Mean associated with predicted proportion of species to go extinct across IPCC scenarios |
| Dangles et al. (41) | Predicted change in population |
| Ellis et al. (42) | Mean associated with predicted change in range (>50% probability of occurrence) across presented scenarios |
| Ellis et al. (43) | Estimated change in predicted range |
| Feuchtmayr et al. (44) | Predicted change in population; time period estimated from IPCC scenarios and mean extinction risk across scenarios used |
| Fish et al. (45) | Mean associated with predicted change in habitat area across sites |
| Gedan and Bertness (46) | Predicted change in percentage cover; time period estimated from IPCC scenarios and mean extinction risk across scenarios used |
| Gomez–Mendoza and Arriaga (47) | Mean associated with predicted change in range across presented scenarios |
| Goulson et al. (48) | Mean associated with predicted change in population across presented scenario. |
| Garcia–Fayos and Bochet (49) | Mean associated with predicted change plant cover across plots |
| Hall–Spencer et al. (50) | Mean associated with predicted change in population with projected pH across distance bands |
| Hilderbrand et al. (51) | Mean extinction risk across bands and presented scenarios |

**Table S1. Cont.**

| Study* | Method of estimating extinction risk |
|---|---|
| Hollister et al. (52) | Change in percentage cover; time period estimated from IPCC scenarios and mean extinction risk across scenarios used |
| Hoyle and James (53) | Mean predicted extinction risk across presented scenarios |
| Hughes et al. (54) | Mean associated with predicted change in range scenarios (minor error in presented data corrected) |
| Jarema et al. (55) | Mean associated with estimates of predicted changes in density across presented scenarios |
| Jensen et al. (56) | Mean associated with predicted change in range (>0.75 probability of occurrence) across presented scenarios |
| Lassalle et al. (57) | Predicted change in range |
| Li et al. (58) | Mean associated with predicted change in population across presented scenarios |
| Logan et al. (59) | Mean associated with predicted change in percentage area at risk across years and tree types |
| Malcolm et al. (60) | Mean predicted proportion of taxa extinct across presented scenarios |
| Marrero–Gómez et al. (61) | Taxa predicted to go extinct |
| Maschinski et al. (62) | Mean associated with predicted change in population across presented scenarios and sites |
| O'Neill et al. (63) | Predicted change in range |
| Portner and Knust (64) | Mean associated with predicted changes in population across presented scenarios |
| Raxworthy et al. (65) | Proportion of taxa predicted to go extinct; time period estimated from IPCC scenarios and mean extinction risk across scenarios used |
| Saltz et al. (66) | Mean predicted probability of extinction across presented scenarios |
| Sekercioglu et al. (67) | Mean associated with predicted change in range across presented scenarios |
| Shoo et al. (68) | Mean proportion of taxa predicted to go extinct across presented scenarios |
| Thuiller et al. (69) | Derived using estimated proportion in each IUCN risk category |
| Vargas et al. (70) | Estimate derived from predicted change in SST and relationship between SST and percentage change in numbers |
| Virkkala et al. (71) | Mean associated with predicted changes in range across presented scenarios |
| Vos et al. (72) | Mean associated with predicted changes in range across presented scenarios |
| Walker et al. (73) | Predicted change in effect size of cover; time period estimated from IPCC scenarios and mean extinction risk across scenarios used |

*The study numbers in parentheses correspond to numbers shown in Fig. S2.


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**Table S2. Effects of climate change impact type on expected extinction probability estimates**

| | Estimate (−SE to +SE) | | Sample size | |
|---|---|---|---|---|
| | Observed | Predicted | Observed | Predicted |
| Changes in ocean circulation patterns | 0.196* (0.085–0.393) | 0.637† (0.404–0.820) | 3 | 1 |
| Temperature and rainfall change | 0.116‡ (0.060–0.211) | 0.045* (0.021–0.096) | 92 | 178 |
| Responses to habitat change | 0.225* (0.121–0.379) | 0.275§ (0.107–0.545) | 29 | 2 |
| Changes in sea ice coverage | 0.308* (0.213–0.423) | — | 6 | 0 |
| Changes in ocean acidity | — | 0.042† (0.028–0.062) | 0 | 1 |

*Not significant.
†$P < 0.001$.
‡$P < 0.05$.
§$P < 0.01$.

**Table S3. Estimates of expected extinction probabilities for a range of relationships between reductions in population size and extinction probabilities**

| | Decline* | | | Extinction probability† | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | CR | EN | VU | CR | EN | VU | Slope* | Intercept† | Mean extinction risk of observed responses | Mean extinction risk of predicted responses |
| Actual | 0.8 | 0.5 | 0.3 | 0.500 | 0.200 | 0.100 | 13.284 | −6.79251 | 0.147 | 0.067 |
| 2 | 0.8 | 0.5 | 0.3 | 0.637 | 0.480 | 0.426 | 13.284 | −5.00000 | 0.238 | 0.143 |
| 3 | 0.8 | 0.5 | 0.3 | 0.384 | 0.079 | 0.032 | 13.284 | −8.00000 | 0.101 | 0.048 |
| 4 | 0.8 | 0.5 | 0.3 | 0.403 | 0.126 | 0.070 | 12.000 | −6.79251 | 0.120 | 0.058 |
| 5 | 0.8 | 0.5 | 0.3 | 0.563 | 0.376 | 0.327 | 12.000 | −5.00000 | 0.212 | 0.121 |
| 6 | 0.8 | 0.5 | 0.3 | 0.274 | 0.045 | 0.022 | 12.000 | −8.00000 | 0.076 | 0.045 |
| 7 | 0.8 | 0.5 | 0.3 | 0.608 | 0.329 | 0.159 | 15.000 | −6.79251 | 0.184 | 0.084 |
| 8 | 0.8 | 0.5 | 0.3 | 0.716 | 0.604 | 0.574 | 15.000 | −5.00000 | 0.272 | 0.174 |
| 9 | 0.8 | 0.5 | 0.3 | 0.514 | 0.157 | 0.052 | 15.000 | −8.00000 | 0.135 | 0.055 |

IUCN categories: CR, critically endangered; EN, endangered; VU, vulnerable.
*All declines are over 10 y.
†Extinction risk period varies by category (CR = 10 y, EN = 20 y, and VU = 100 y).