

The SAFE index: using a threshold population target to measure relative species threat

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The International Union for Conservation of Nature (IUCN) Red List is arguably the most popular measure of relative species threat, but its threat categories can be ambiguous (eg “Endangered” versus “Vulnerable”) and subjective, have weak quantification, and do not convey the threat status of species in relation to a minimum viable population target. We propose a heuristic measure that describes a “species’ ability to forestall extinction”, or the SAFE index. We compare the abilities of the SAFE index with those of another numerically explicit metric – percentage range loss – to predict IUCN threat categories using binary and ordinal logistic regression. Generalized linear models showed that the SAFE index was a better predictor of IUCN threat categories than was percentage range loss. We therefore advocate use of the SAFE index, possibly in conjunction with IUCN threat categories, because the former indicates the “distance from extinction” of a species, while implicitly incorporating population viability as a variable.

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Conservation biologists have long studied the processes underlying species’ extinctions and have sought to devise ways to prevent or mitigate extinctions resulting from human impacts. Recent debates over the likely magnitude of the current extinction crisis have largely focused on the proportion of all species that could disappear during this century (eg Brook *et al.* 2006a; Laurance 2007; Bradshaw *et al.* 2009). However, species’ extinctions due to anthropogenic factors are just the endpoint conservationists wish to avoid. Today, many species are declining across large swathes of their former geographic ranges, and some species’ populations are becoming so seriously diminished in numbers that they are less

likely to withstand random catastrophes (Ewens *et al.* 1987) or maintain their original functional roles in ecosystems (Larsen *et al.* 2005) and their evolutionary potential (Franklin and Frankham 1998).

Earlier terms describing the imperiled status of species that had undergone major declines include the *living dead* (Janzen 1986) and *extinction debt* (Tilman *et al.* 1994), both of which embody the notion of short-term persistence but a long-term consignment to extinction. *Local extinction* or *extirpation* describes the loss of local populations (eg Laurance 1991; Pimm and Askins 1995), but typically has a narrow frame of reference, such as a particular island or habitat fragment. The concept of *ecological extinction* was coined in reference to the reduction of a species to such low abundance that it “no longer interacts significantly with other species” (Estes *et al.* 1989), but determining the critical threshold-abundance values for specific species can be impractical.

The most widely used barometer of a species’ threatened status is the International Union for Conservation of Nature (IUCN) Red List (www.iucnredlist.org), which classifies species at high risk of global extinction through an explicit, objective, and semi-quantitative framework (IUCN 2010). However, IUCN threat categories such as “Endangered” and “Vulnerable” might not be easily differentiated by the general public, conservation donors, and policy makers without an associated numerical indicator. Furthermore, the IUCN threat categories do not reflect the distance of an extant population of a given species from an arbitrary but risk-averse minimum viable population (MVP) size required for long-term persistence and evolutionary potential (Traill *et al.* 2010).

Some claim that population extinctions (extirpations) are more useful proxies of diminishing biological capital

In a nutshell:

- We developed the “species’ ability to forestall extinction” (SAFE) index, which incorporates a benchmark population target for long-term species persistence
- This index better predicts the widely used IUCN Red List threat categories than do previous measures, such as percentage range loss
- A combined approach – IUCN threat categories together with the SAFE index – is more informative than the IUCN categories alone and provides a good proxy for gauging the relative “safety” of a species from extinction

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than are species extinctions (Ceballos and Ehrlich 2002), especially when it can take a long time for threatened species to be recognized as officially extinct (ie failure to detect the species despite years of searching; McInerney *et al.* 2006). Here, we advocate the use of a more heuristic measure of relative threat that describes a “species’ ability to forestall extinction”, or the SAFE index:

$$\text{SAFE index} = \log_{10}(N) - \log_{10}(\text{MVP}_t) \quad (\text{Eq 1})$$

where N is the species’ population estimate throughout the species’ known range (ie all populations combined) and MVP_t is an empirically supported threshold MVP target, which is currently set at 5000 individuals according to median demographic and genetic estimates of MVP-size requirements among widely different taxonomic groups (Brook *et al.* 2006b; Traill *et al.* 2007, 2010). On precautionary grounds, we suggest using the lower confidence-limit estimates of N and the upper confidence-limit for MVP size, where such estimates exist for the species of interest and are considered statistically robust (Traill *et al.* 2010).

One might argue that a numerically explicit measure of biodiversity loss already exists in the form of percentage range loss, an index used by Ceballos and Ehrlich (2002) to compare historical and present distributions of 173 declining mammal species across six continents. We therefore investigated whether the SAFE index can better predict relative species threat (according to the IUCN Red List) than does percentage range loss.

We constructed binary and ordinal logistic regressions to determine which of the two metrics, the SAFE index or percentage range loss, better predicts the IUCN threat categories of mammal species for which extant population sizes were available (95 of 173 species from Ceballos and Ehrlich 2002) on the Red List website (IUCN 2010). We extracted percentage-range-loss data (current range area/original range area) from Ceballos and Ehrlich (2002). Our binary responses consisted of “threatened” and “near/not threatened” after pooling four (“Extinct”, “Critically Endangered”, “Endangered”, and “Vulnerable”) and two (“Near Threatened” and “Least Concern”) IUCN threat categories, respectively. Our ordinal responses consisted of six IUCN threat categories, ranked according to their indicative risk levels (ie “Extinct” to “Least Concern”). In the binary logistic regression, we fitted generalized linear models (GLMs) using the R package 2.10.1 (R Development Core Team 2010), assigning to candidate models (Table 1) a binomial distribution and logit link function. To control for phylogenetic relatedness, we also fitted generalized linear mixed-effect models (GLMMs) to the data using mammalian order (ORDER; Table 1) as a random effect (Bradshaw and Brook 2010). For the ordinal logistic regression analysis, we used the *polr* function (implemented in the MASS library of the R package), which fits a proportional-odds logistic regression model to an ordinal factor response. We calculated the relative likelihoods and weights of models using Akaike’s information criterion corrected for small sample sizes (AIC_c ; Burnham and Anderson 2002). We compared relative statistical evidence among models using the information–theoretic evidence ratio (ER), which is the AIC_c weight of one model divided by another. The ER is a concept akin to Bayesian odds ratios (McCarthy 2007) and is preferable to a classic null-hypothesis significance test because the likelihood of the alternative model is explicitly evaluated (Bradshaw and Brook 2010). For each model, we also calculated the percentage deviance explained (%DE) as a measure of goodness-of-fit, and compared each model’s %DE to determine the proportion of variance in the response that was attributable to each predictor.

We provide SAFE indices for 95 mammal species in WebTable 1. Using an MVP target of 5000 individuals on a logarithmic scale (Traill *et al.* 2010), we calculate that an extinct species would have a SAFE index of -3.7 (ie assuming “extinction” equates to $N = 1$ because $\log_{10}[0]$ is unresolvable; Figure 1). Such a non-linear scale is particularly beneficial for the management of species with low population sizes, because slight population fluctuations will result in acute changes in SAFE indices that can help trigger urgent conservation interventions. Negative SAFE indices indicate that a species is below the threshold MVP target of 5000 individuals (eg if $N = 4000$, then SAFE index = -0.1), whereas positive SAFE indices indicate the species is above that threshold (eg if $N = 6000$, then SAFE index = 0.08).

Table 1. Generalized linear model (GLM) and generalized linear mixed-effect model (GLMM) sets used to examine the relationship between the probability (Pr) of a species being threatened for 95 mammal species and predictors

Model	k	$-LL$	ΔAIC_c	$w\text{AIC}_c$	%DE
GLM					
$\text{Pr}(\text{threat}) \sim \text{SAFE index}$	2	-22.89	0.00	1.00	59.0
$\text{Pr}(\text{threat}) \sim \% \text{ range loss}$	2	-46.37	46.96	0.00	16.8
$\text{Pr}(\text{threat}) \sim I$	1	-55.75	63.65	0.00	0.00
GLMM					
$\text{Pr}(\text{threat}) \sim \text{SAFE index} + (1/\text{ORDER})$	3	-22.89	0.00	1.00	56.4
$\text{Pr}(\text{threat}) \sim \% \text{ range loss} + (1/\text{ORDER})$	3	-45.94	46.11	0.00	12.4
$\text{Pr}(\text{threat}) \sim I + (1/\text{ORDER})$	2	-52.46	57.02	0.00	0.00

Notes: Only single-term models were considered to test the relative ability of the SAFE index versus percentage range loss in predicting extinction threat (threat). The analytical theme represented by each model (SAFE index, % range loss, the intercept-only model, and mammalian order [ORDER] as a random effect), and the information–theoretic ranking of models investigating the predictors of mammal IUCN threat categories according to Akaike’s information criterion corrected for small sample size (AIC_c) are shown. k = number of parameters, $-LL$ = maximum log-likelihood, ΔAIC_c = difference in AIC_c for each model from the most parsimonious model, $w\text{AIC}_c$ = AIC_c weight, and %DE = percent deviance explained in the response variable by the model under consideration. Two data points were removed for the GLMM because there was only one representative species in its respective mammalian order: riverine rabbit (*Bunolagus monticularis*) and Asian elephant (*Elephas maximus*).

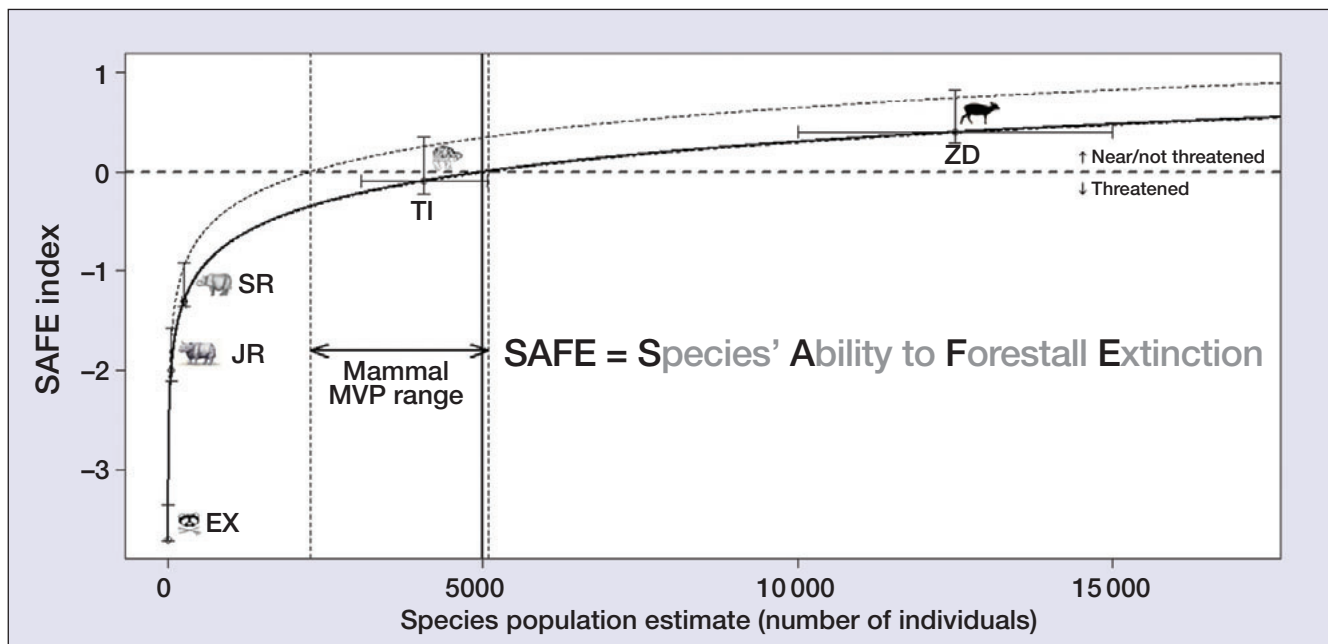


Figure 1. Plots of SAFE indices against species population estimates with: (1) an empirically supported threshold minimum viable population (MVP) target (solid line and curve; 5000 individuals according to Traill *et al.* 2010); and (2) lower and upper 95% confidence limits of mammal-specific MVP thresholds (dashed lines and curves; 2261 and 5095 individuals, respectively, according to Traill *et al.* 2007). An extinct species (EX), the Javan rhinoceros (JR; *Rhinoceros sondaicus*), Sumatran rhinoceros (SR; *Dicerorhinus sumatrensis*), tiger (TI; *Panthera tigris*), and zebra duiker (ZD; *Cephalophus zebra*) are highlighted (with vertical and horizontal confidence intervals) to illustrate their decreasing relative threat and increasing potential for long-term persistence (from left to right).

If taxon-specific SAFE indices incorporating population and MVP-size uncertainties are desired, then species abundance estimates (N) can be substituted with lower and upper confidence-limit estimates (eg 1996 and 2447 for Grevy's zebra [*Equus grevyi*], respectively; WebTable 1), whereas the MVP_{*i*} of 5000 individuals can also be replaced by the lower and upper 95% confidence limits of taxon-specific MVP thresholds (eg 2261 and 5095 for mammals, respectively; Traill *et al.* 2007). To incorporate these differences, we provide three additional variants of the SAFE index, to represent a greater range of uncertainty (WebTable 1); as before, we fitted both GLMs and GLMMs to these indices, to determine their relative capacity to predict Red List threat categories for mammals.

Binary logistic regression revealed that the SAFE index is a better predictor of mammal IUCN threat categories than percentage range loss (ie the former had higher model weights and described ~59% of the deviance, as compared with only ~17% for the latter; Table 1). Despite including ORDER as a random effect, GLMM results were similar: model weights were identical and the %DE shifted only slightly (Table 1). The model with the SAFE index also had far higher bias-corrected support relative to the model with only percentage range loss ($ER = 1.58 \times 10^{10}$ times providing as much support). Similarly, ordinal logistic regression showed that the SAFE index was a better predictor of relative species threat than percentage range loss; the former had a higher model weight (0.97 versus 0.03) and explained a

higher percentage of deviance in the probability of being threatened (6% versus 4%; %DE values here are lower than those in the binomial models because the variance is spread over more IUCN threat categories in the ordinal regression). GLMs and GLMMs showed that the three uncertainty variants of the SAFE index were still far better predictors of mammal threat status than percentage range loss, but still did not outperform (in terms of %DE) the original SAFE index based on an MVP value of 5000 individuals (WebTable 2).

■ Conclusions

The SAFE index is attractive for at least three reasons. First, it has a far superior ability to predict IUCN threat categories, as compared with the percentage range loss of a species (Table 1). Second, it does not rely on the difficult-to-obtain demographic data needed to construct detailed population viability analyses necessary for predicting extinction risk. Finally, it leverages some recent meta-analyses on the MVP size estimates for well-studied groups (Traill *et al.* 2007).

On the basis of numeric, meta-analytic, and genetic evidence, MVP estimates (standardized to a time scale of 40 generations and 99% persistence probability) show marked consistency among taxa whose populations range around 5000 adult individuals (Traill *et al.* 2007, 2010). Whether practitioners choose this standard MVP value and a simple median population-size estimate for target species, or instead elect to use more conservative values,

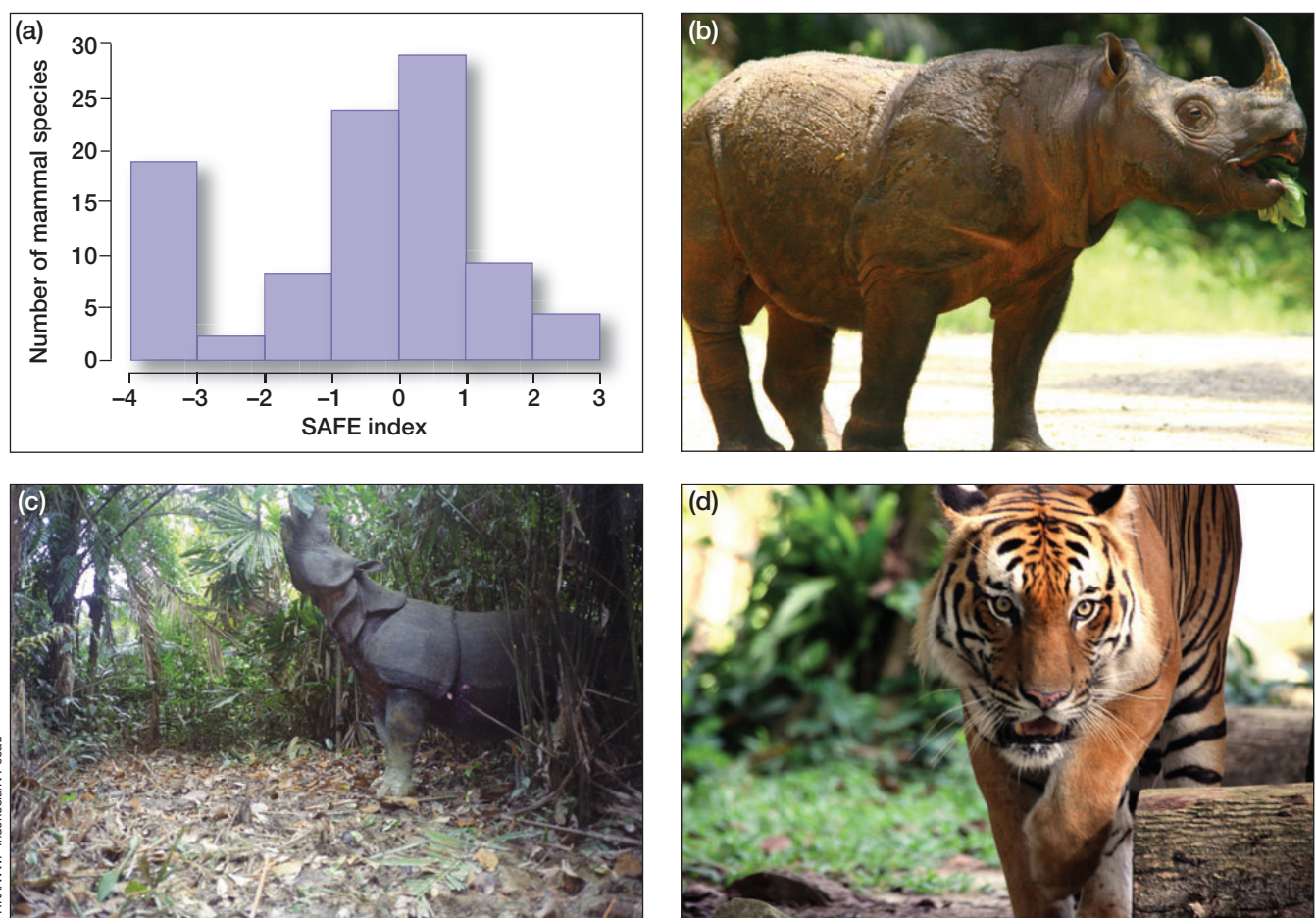


Figure 2. (a) Histogram of SAFE indices across the 95 mammal species in our analysis, indicating ~21% close to extinction (ie SAFE indices < -2) and ~58% at “tipping points” (ie SAFE indices between 1 and -1). Practitioners of conservation triage may want to prioritize resources on (b) the Sumatran rhinoceros (*Dicerorhinus sumatrensis*) instead of (c) the Javan rhinoceros (*Rhinoceros sondaicus*) (-1.36 versus -2.10 , respectively). Alternatively, donors with limited resources may want to channel their conservation efforts toward (d) the tiger (*Panthera tigris*), a species at the “tipping point”, with a SAFE index of -0.21 .

will be dictated by their acceptance of the inherent uncertainties. Regardless, the SAFE index provides a more meaningful and fine-grained interpretation of the relative threat of species extinction than do the IUCN threat categories alone. The IUCN has yet to base its threat categories on predictions from population viability analyses because of inadequate data or models for most listed species (Traill *et al.* 2010).

We believe that the SAFE index could serve as a quantitative measure of relative threat status that can be more readily understood by the general public, donors, and policy makers, who may not appreciate the need to consider population viability in conservation and who do not understand the IUCN categorical classifications. For example, the Asian elephant (*Elephas maximus*) has a SAFE index of 0.92 ($N = 41\,410$), whereas the index for tigers (*Panthera tigris*) is -0.21 ($N = 3062$). Although both species are classified as “Endangered” according to IUCN (2010), the latter arguably warrants more urgent conservation attention (see Clements *et al.* 2010). However, this does not necessarily mean we should reduce efforts to protect endangered species with positive

SAFE indices, such as the Asian elephant, because other threats such as population fragmentation and poaching may be higher for certain species.

More than half (58%) of all mammal species in our analyses appear to be at vulnerability thresholds, or “tipping points”, with SAFE indices between 1 and -1 (Figure 2). Donors with limited resources might wish to focus on such species; the tiger, for instance, has a SAFE index of -0.21 (Figures 1 and 2). Roughly one-quarter of the species in our analysis are very close to extinction, with SAFE indices below -2 (Figure 2). Under such desperate circumstances, those considering conservation triage (Walker 1992) might elect to channel resources toward species such as the Sumatran rhinoceros (*Dicerorhinus sumatrensis*) rather than the precarious Javan rhinoceros (*Rhinoceros sondaicus*); these species have SAFE indices of -1.36 and -2.10 , respectively (Figures 1 and 2).

When communicating the danger of extinction, the threat status of an imperiled species becomes much more apparent through the use of the SAFE index in conjunction with IUCN Red List categories. For this reason, we

advocate including the SAFE index in future Red List classifications. However, the use of a standard MVP target for all species will always be controversial and such general principles have their limitations when population context (eg connectivity, degree of habitat fragmentation, source–sink dynamics, and disease susceptibility) can overwhelm extinction risk arising from stochastic disturbances. Empirically based alternatives to a standard MVP might exist and could work equally well under the same “distance” principle embodied in the SAFE index – our key point is that species should be assigned a continuous and quantifiable index of “distance from extinction”.

Ultimately, the SAFE index serves as a scientifically defensible rule of thumb when complete demographic data are unavailable for a species, as is usually the case. As our empirical data show, threatened species with deceptively large populations – including those with thousands of individuals – can still have a high probability of eventually succumbing to global extinction. We should therefore avoid complacency and heed the best evidence available while attempting to avoid the permanent loss of these species.

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