Africa’s Elephants
(*Loxodonta africana and Loxodonta cyclotis*)

SUPPLEMENTARY MATERIAL

Modelling Approach

We adopted a data-led model-based approach that differed from previous assessments for the species. Our intention was to increase the rigor, reproducibility and transparency behind the Red List categorization of the African elephant. The data available for this assessment were extracted from the African Elephant database (AED) and include all surveys up to and including 2015, supplemented with pre-AED survey reports from the literature (described in Data on page 6). The complexity of the model was matched to the information content of the data, thus avoiding the need for unsupported assumptions concerning the underlying population dynamics. The model can be viewed as a mechanism for extracting and summarizing information from the survey data which varies in the methodology of collection and the accuracy and precision of the estimates.

A random-effects hierarchical regression was developed that estimated the continental change in African elephant numbers from log-linear trends fitted to survey density estimates at multiple sites across the continent. African elephant density was modelled rather than elephant numbers since the survey area size was not constant over time for most survey sites. In compliance with the Guidelines for Using the IUCN Red List Categories and Criteria (version 14; IUCN SPC 2019), which stipulates that for a geographically dispersed population, the overall reduction should be calculated as a numbers weighted average across sites: “All available data should be used to calculate a reduction as an average over all subpopulations, weighted by the estimated size of each subpopulation at the beginning of the period” (Section 4.5.4, page 38, “*Estimating overall reduction*”), the global species trend was calculated as a weighted average trend across sites. Weights per site were obtained by converting the predicted densities at the beginning of the period (see Assessment timeframe page 6) into numbers using the modal survey area size per site. If there was more than one mode, the maximum was used.

The model assumed African elephant population dynamics to be a function of site-specific growth rates, which were estimated as the product of intrinsic growth and extrinsic mortality. A hierarchical structure allowed trend information to be shared across sites in a manner that depended on the quantity and quality of data: sites with good data informed the trend estimates for sites with poor data. If there were insufficient data at a site to estimate a trend, then the country level trend would be applied. Similarly, if there were insufficient data in a country, then the global trend estimate would prevail as the best estimate available. No account was taken of geographical proximity in the sharing of information between sites.

Model Description

We start with a model of the numbers per population or survey site N_i over time t as a function of an intrinsic growth rate r and a mortality rate $f(\boldsymbol{\varphi}_i, t)$, specified as a function of parameter vector $\boldsymbol{\varphi}_i$ and time:

$$\frac{d}{dt}N_i = N_i\left(r - f(\varphi_i, t)\right)$$

If we assume no density dependent effects and a constant additive mortality then $f(\boldsymbol{\varphi}_i, t) = m_i$ and the solution is:

$$ln\left(N_i(t)\right) = t(r - m_i) + ln\left(N_i(0)\right)$$

where ln(N_i (0)) is the initial state. We refer to this model as the “log-linear” model. To fit the model to density data, it can be written as a regression on the density $D_i = N_i/A_i$:

$$ln\left(D_i(t)\right) = t(r - m_i) + ln\left(D_i(0)\right) - ln\left(\Delta A_i(t)\right) + \varepsilon_i$$

where $ln\left(\Delta A_i(t)\right)$ is the relative change in range area size for the population being sampled and ε_i is an error term. Assumptions concerning the range size and how it may (or may not) be correlated with population numbers is an important consideration for the modelling, which is covered in more detail below (see Model Assumptions). To parameterize the model so that it can be fitted to data at the continental level, we include the country subscript j and specify a sub-model for the mortality:

$$m_{ij} = \alpha_0' + \alpha_j + \epsilon_i$$

with a global intercept term α_0', a country specific mortality α_j and a site-specific error. The country and site specific terms were both assumed to follow normal distributions and treated as nested random effects, meaning that their variance terms were estimated. We can then write the multiplicative growth rate per site as:

$$ln\left(\lambda_{ij}\right) = \alpha_0 - \alpha_j - \epsilon_i$$

with $\alpha_0 = r - \alpha_0'$. Therefore:

$$ln\left(D_{ij}(t)\right) = t.\ln(\lambda_{ij}) + ln\left(D_{ij}(0)\right) - ln\left(\Delta A_{ij}(t)\right) + \varepsilon_{ij}$$

Estimated model parameters were the density intercept per site $D_{ij}(0)$, the global trend parameter α_0, and the country and site-specific random effects α_j and ϵ_i (including their variance terms).

An alternative model was also investigated in which the mortality was allowed to change linearly over time: $f(\boldsymbol{\varphi}_i, t) = m_i + h_i t$. The solution to the population dynamics equation is then:

$$ln(N_{it}) = t(r - m_i - h_i t/2) + ln\left(N_i^0\right)$$

In this case, the growth rate is:

$$ln\left(\lambda_{ij}\right) = \alpha_0 - \alpha_j - \epsilon^{\alpha}{}_i - \left(\beta_0 + \beta_j + \epsilon^{\beta}{}_i\right).t$$

with additional regression parameters β_0, β_j and $\epsilon^{\beta}{}_i$, and which yields a second-order change in the log-density over time. We refer to this model as the “log-polynomial” model.

Model Fitting

Fits of the model to non-zero survey data were performed using a log-normal likelihood for the observation process (i.e., the observed density values were assumed to follow a log-normal distribution around the model predictions). Parameters were estimated within a Bayesian framework using Stan (Stan Development Team. 2018. *Stan Modeling Language Users Guide and Reference Manual*, Version 2.18.0). Convergence was assessed visually (not shown), and fits to the data checked using posterior predictive simulation (Figure 1).

A small number of zeros were present in the survey data and used to calculate the parameter θ_i, which is the maximum likelihood estimate of the binomial probability of a positive survey per site. This was generated analytically and not included in estimation of the trend per site. It was however used as part of the weighting per site when generating an overall numbers weighted average of the trend.

Model selection

To select the best performing model, we used the mean prediction error, which is a measure of the model’s ability to predict the empirical data. For each draw *p* from the posterior, the mean prediction error is:

$$MPE_p = \sum_k \frac{\left|\hat{y}_{kp} - y_k\right|}{y_k}$$

where the summation is across all *k* surveys, y_k are the data and $\hat{y}_{kp}$ is generated using posterior predictive simulation. Comparing the distributions of MPE for the log-linear and log-polynomial models we observed that the prediction error was similar for the log-polynomial model for both species. We therefore concluded that the additional parameters do not yield any noticeable improvements to the model fit, and we therefore selected the log-linear model as the most parsimonious estimator of the decline. We report results only for this model.

Trend estimation

Following fits of the model, estimates of the trend were obtained as numbers-weighted averages of the decline per site. Using model-based estimates of the initial population size (N_{ij}^{0}), and final population size in year Y ($N_{ij(t=Y)}$), the decline per site is:

$$\Delta N_{ij} = 1 - \frac{N_{ij(t=Y)}}{N_{ij}^{0}}$$

As a weighted average, with the initial population size providing the weights, the estimated global decline is:

$$\Delta N = 1 - \frac{\sum_{ij} N_{ij(t=Y)}}{\sum_{ij} N_{ij}^{0}}$$

Values for N_{ij}^{0} and $N_{ij(t=Y)}$ were generated as the predicted densities at those respective time points multiplied by the modal survey area size, multiplied by θ_i. The parameter θ_i down-weights the contribution of a site to the overall trend by the probability that elephants have been observed at that site over the survey time series. Since the number of zero survey estimates was small, θ_i was typically close to one.

To estimate population change over the periods of relevance to the assessment, the initial population size in 1984 and 1965 was used for the Forest and Savanna species respectively (based on generation times and period of interest as described in Assessment timeframe page 6). The full posterior distribution of the declines for each species is given in Figure 2. The median of these distributions was used to categorize the decline according to the Red List criteria (Table 1).

Model Assumptions

Mortality assumptions

We assume that mortality is site specific and constant over time, which leads to a log-linear change in density over time. This is the most parsimonious model for fitting the available data. However, there is independent evidence (not included in the current analysis) that mortality has oscillated dramatically in relation to human harvest for African Savanna Elephants over the last 40 years, though differently by site in respect to degree and time. To model this, more complicated mortality sub-models would be required. From fits of the log-polynomial model, we concluded that higher order terms could not be supported by the currently available data.

Correlations between range area and population number

Inflated population densities due to compression effects are difficult to quantify and account for analytically. It is likely that some elephant populations may have been compressed into protected areas to avoid threats in the broader landscape, resulting in increased densities within the surveyed areas as elephant extirpation occurred in parts of their prior range. While it is clear this has happened in East and Central Africa, we lack definitive information on when, where and the extent to which this occurred across sites and therefore have not explicitly incorporated such processes in this assessment. We assume that this process makes our estimates of population change underestimates of declines given surveys focus on core, protected areas and often do not cover outlying areas, which often are areas of lower or no protective status.

When considering reliability of the model outputs, if the range area changes when the population size changes then this likely will influence whether local density is a reliable indicator of the overall change in numbers. For purposes of illustration, consider two alternate scenarios:

1. The range area is constant (i.e., independent of elephant numbers). Therefore, when the population changes in size, the average density will change linearly. In modelling this scenario, we can fit directly to the survey density data and range area size data are not needed.
2. The range size expands and contracts with population number. This could result in a more stable density, meaning changes in population size will not be reflected directly in changes in the density. Such a signal is probable in some surveys, since surveys are non-randomly placed and often deliberately focused on areas with known high densities of elephant. In this scenario, some representation of how the range sizes have changed needs to be included in the modelling.

Our best information concerning changes in the population range size is from the survey area size, precisely because surveys are often centered (for reasons of financial expediency) on regions of known high elephant densities. Distinguishing between conditions reflecting Scenarios 1 and 2 above relates to the impact of ignoring relative changes in survey area size in the right-hand side of the model. If Scenario 1 is in fact true, then inclusion of a change in the survey area size likely will result in a trend in the density even when the population size is constant. Conversely, if Scenario 2 is true, then exclusion of a change in the area size may **not** invoke a trend in the density even if there has been a change in numbers. Given these scenarios, **ignoring survey area size changes may cause the model to be more conservative** (i.e., it is less likely to overestimate the population decline): if the density index is hyper-stable because of changes in range size, but we assume that the range size is constant, the model is less likely to report a trend. In lieu of further analyses, and because it is more conservative, **we therefore make an implicit assumption that the range size is constant** (i.e., $\Delta A_i(t) = 1$, which means that area size changes can be excluded from the modelling)."

Within-survey error

Each survey data record has associated observation error (see Data quality considerations below), the reporting of which was captured in an accuracy metric reported for some surveys. These metrics were not considered directly by the model, which treated the residual error (the difference between observed and model-predicted density values) as a combination of: 1) inaccurate surveys; and 2) an inaccurate representation of reality by the model. The second of these will be larger, meaning that the residual error estimated by the model will largely be the result of using such a simple model of the population dynamics. Nevertheless, survey observation error could be included as a constant variance term per survey. If it differed between surveys then the model would fit preferentially to surveys with lower observation error. Disregarding reported survey error, when available, amounts to an implicit assumption that survey error is similar between surveys and/or negligible compared to the structural error that results from simplicity of the model.

Zero observations

The model was fit to survey data at the site level and on a log-scale, and therefore could not account for zero observations when estimating the trend per site. However, the overall number and percentage of zero observations in the data was small and these were therefore excluded from the analysis (58 survey estimates were excluded and 866 survey estimates remain for the analysis of the African Savanna Elephant; 24 survey estimates were excluded and 343 survey estimates remain for the analysis of African Forest Elephant).

Data

The primary source of African elephant population estimates and distribution for this assessment is the IUCN SSC AfESG African Elephant Database (AED), a comprehensive repository of data from survey reports and questionnaires from 37 African elephant range states beginning in 1992 through 2015 (survey data are available as early as the late 1980s).

Survey data from after 2015 are not included in this assessment (no surveys have been evaluated and entered into the AED by the AfESG since the publication of the AESR 2016). Data on elephant populations pre-dating the AED are compiled from original sources largely found in the IUCN SSC AfESG African Elephant Library (AEL). Although we consider our search for data pre-AED to be relatively comprehensive, we probably did not discover all possible population survey reports; attempts to find raw survey data to derive missing values were cursory if the survey reports were not available in the AEL. Overall, the frequency and timing of surveys varied greatly across sites. The earliest survey in the African Savanna Elephant dataset was 1964; for the African Forest Elephant dataset, it was 1974.

Due to our reliance on data from survey reports and questionnaires, we omitted extrapolated estimates to unsurveyed areas. Surveys have typically focused on protected areas and their immediate surroundings as these tended to have the highest densities of African elephants. Before 1980, experts thought that African elephants were continuously distributed across Central Africa and widely distributed across East Africa including much unprotected range. African elephants were subsequently mostly extirpated from these unprotected areas; moreover, there is limited survey data for this range or quantitative documentation of this extirpation. Therefore, such extirpations are not directly quantifiable and, as a result, not accounted for in this assessment.

This assessment can thus be considered **methodologically conservative** given the exclusion of non-survey based estimates of decline and range loss, and the strong influence of well surveyed, high density sites on model results.

Assessment timeframe

In accordance with subcriterion A2, this Red List assessment derives an estimated population trend for a period spanning three generations. For African elephants, this requirement extends population projection at least one generation prior to the onset of survey data on the species. Systematic surveys of many populations did not begin until the mid-1970s for African Savanna Elephants and mid-1990s for African Forest Elephants, with increasing numbers of sites included in the dataset as time progressed. Rather than project the model back in time, we assumed no population change from 1940–1965, corresponding to the first generation (25 years) of the assessment for the African Savanna Elephant; its population trend was therefore estimated from survey data for the period 1965–2015. For the African Forest Elephant, we assumed no population change from 1922–1983, corresponding to the first and second generation (62 years as generation length is 31 years) of its assessment and its population trend was therefore estimated from survey data for the period of 1984–2015.

Data quality considerations

Survey data are included in the trend modeling if a population estimate, actual survey area size, location and source was available (i.e., a complete record) and attempts were made to obtain a complete record when information was missing in the AED. Extrapolations made in survey reports are omitted because they lacked the required attributes of a complete survey.

Population estimate data vary in quality and according to survey method (e.g., identification of individual animals, aerial counts, dung counts and guesses). The AED classifies population estimates according to the level of certainty (i.e., reliability scale ranging from A (highest) to E (lowest) that can be placed on a given number as determined by a dedicated Data Review working group of the AFESG on the basis of the survey method employed, how it was carried out and reported for inclusion in the AED). For this assessment, if an estimate was assigned Reliability A-D then it is included in the analysis. If it was assigned a Reliability E, which was the case for 43 survey estimates for the African Savanna Elephant and 34 survey estimates for the African Forest Elephant, it was excluded. Reliability E is designated as an “other guess” (Thouless *et al*. 2016) that was not informed by clearly explained logic or data. However, we applied one exception: small population estimates of ≤50 elephants with Reliability E were retained under the assumption that these represent near-extirpations of populations that logically would not be surveyed with greater effort due to expected practical, economic and precision challenges of surveying animals at low densities. This applied to 26 survey estimates for the African Savanna Elephant and 38 survey estimates for the African Forest Elephant; these cases were retained in the analysis. In the case of pre-AED data, estimates were included even though there was no Reliability score associated with the data. 8.8% of the Savanna Elephant and 6.8% of the Forest Elephant estimates included in our analysis had no Reliability score assigned; all of these pre-dated 1992 when the AED and its reliability scoring process began.

Data preparation

Site

Survey data were entered into the AED by “Input Zone” which may be a national park, a game reserve, communal land, national forest, game management area, hunting block, wildlife sanctuary, forest concession, “surrounding areas” *etc*. or any combination of the above. Combinations sometimes appear as “ecosystems” or “landscapes” in the AED. We organized pre-AED survey data similarly. In savanna regions, pre-AED survey zones were often larger in size than subsequent AED Input Zones and in forest regions the opposite is sometimes apparent. Because the exact name and survey area size of overlapping Input Zones with the same or similar coordinates often appeared to change over time, we designated "site" for the time series analysis in this assessment from the Input Zone as follows. In the simplest case, we assigned Input Zones with the same or similar names, area size and coordinates to a single site. A more complicated case is when the survey area was recorded as an entire "ecosystem" or "landscape" in some years but in others it is entered into the AED as some or all possible subunits thereof. For these cases, the largest discernible survey area (i.e., the "ecosystem") was assigned as the site in years in which all or most subunits of the site were surveyed. Estimates and area sizes were then added together to represent that site population estimate. Every attempt was made to examine original source maps to ensure correct site assignments and all assessors reviewed these for correctness.

Site Area Size

The survey area size may change markedly over time, which may invalidate the numbers time series, since a much larger or smaller survey area size could directly change the survey numbers estimate. To guard against this, we used an arbitrary cut-off: if a single survey area size is >40% different from the modal area size for that site, it was excluded from the time series. This led to removal of 120 survey estimates for African Savanna Elephants and 34 survey estimates for African Forest Elephants. This cut-off is arbitrary but reasonable on the basis of the Assessment Team's collective judgement that such extreme differences could bias the site's density trends.

Number of Mature Individuals

Application of criterion A in the IUCN Red List assessment requires that the population trend of mature individuals of a species be considered; however, population estimates were recorded in the AED and other sources as all individuals. Age structure in free ranging African elephant populations varies over years due to differential mortality and reproduction driven by climatic variation and human disturbance. Juvenile elephants (i.e., immature elephants that have not reached breeding age) generally represent between 40–55% of the population. Due to the older average age of first birth, Forest Elephant populations tend to have higher proportions of juveniles (50–55%) than Savanna species. Given this, we considered mature individuals to be 50% of the population assessed, but note that this assumption will not influence estimation of the trend using the methods described.

Data Assumptions

1) Small variations in the survey area of the same site do not appreciably bias the model outputs.

In repeat surveys of populations, with the same name and approximate area, differences in the extent and area surveyed often occurred. We assume that these changes in the area size did not invalidate the time series.

2) Unsurveyed African elephants, considered to be at low densities, do not appreciably bias the model outputs.

In repeat surveys of populations, where the survey area has decreased substantially over time, some elephants may persist at low densities outside these smaller survey areas and are not accounted for in our analysis.

3) Species assignment based on published and expert sources may result in a limited number of erroneously assigned populations such as some small populations along the savanna-forest transition zone in particular; however, their combined abundance is likely less than 500 individuals. Therefore, we assume that this situation does not fundamentally influence the assessments overall.

4) Our data preparation and cleaning protocols and calculation processes around density and area may result in a few distorted cases but we assume these do not fundamentally influence the categorization of the taxa.

5) The collective variances and assumptions (1–5 in this list) do not appreciably bias the Red List categorization of the species.

Table 1a. Summary of model results for African Savanna Elephant

Population reduction (%) 1940–2015* (IUCN Red List Category)	95% Credible Intervals	Probability that reduction is consistent with IUCN category**			
		CR	EN	VU	Not threatened
60 **ENDANGERED**	15 – 88	0.08	0.63	0.25	0.04

*According to our assumption that there was no population change from 1940 to 1964.
** Determined by the full posterior distribution of model runs and the per cent of posterior samples that fall within each assessment category; not threatened refers to any category below Vulnerable (VU).

Table 1b. Summary of model results for African Forest Elephant

Population reduction (%) 1922–2015* (IUCN Red List Category)	95% Credible Intervals	Probability that reduction is consistent with IUCN category**			
		CR	EN	VU	Not threatened
86 **CRITICALLY ENDANGERED**	58 – 98	0.71	0.28	0.01	0.00

*According to our assumption that there was no population change from 1922 to 1983
** Determined by the full posterior distribution of model runs and the per cent of posterior samples that fall within each assessment category; not threatened refers to any category below Vulnerable (VU).

Table 2. Estimated numbers and per cent reduction per site over three generations for African Savanna Elephants *(follow this link to download a csv version of the table).*

Table 3. Estimated numbers and per cent reduction per site over three generations for African Forest Elephants *(follow this link to download a csv version of the table).*

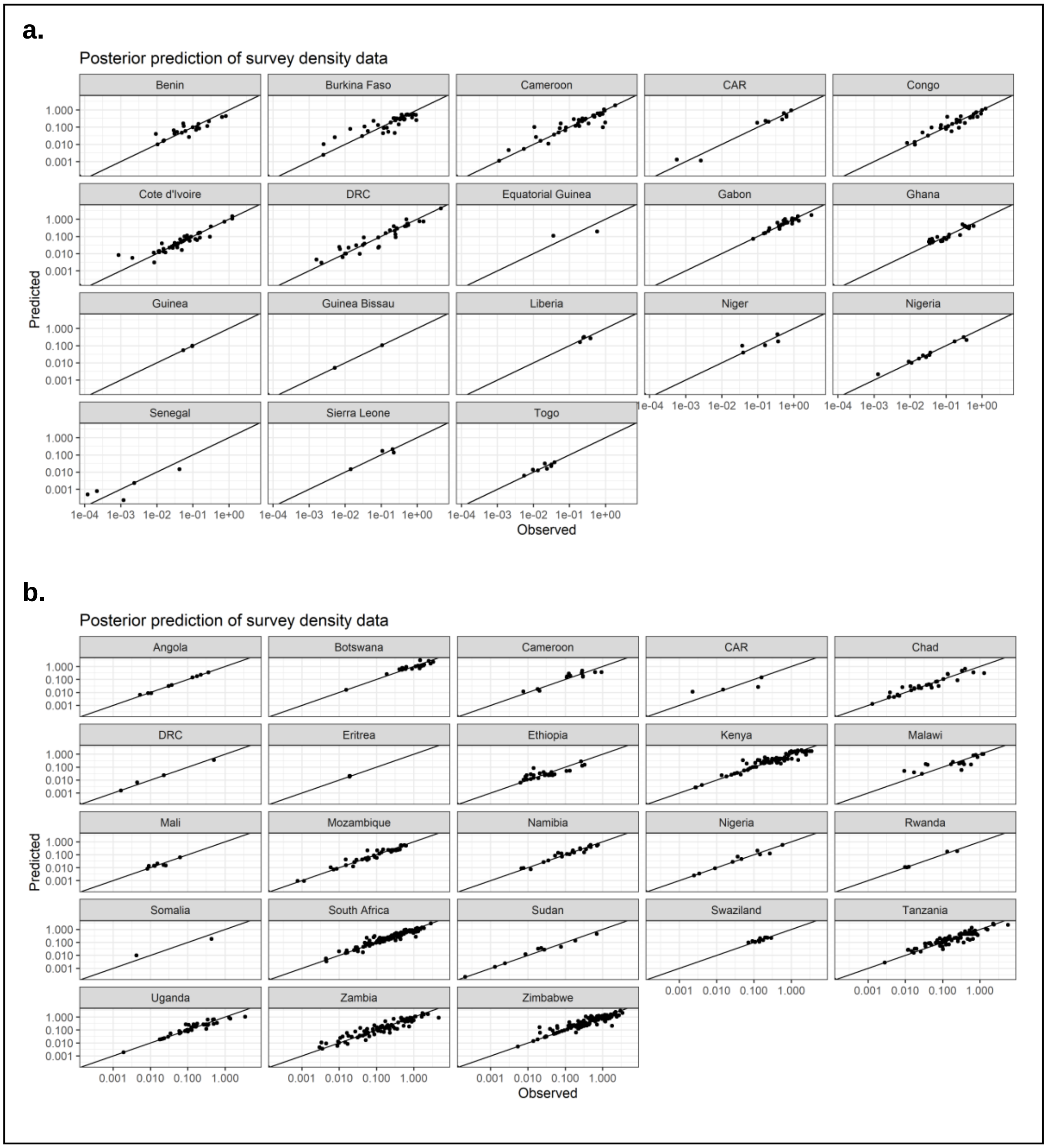

Figure 1. Posterior Predictive Checks of Model for (a) African Savanna Elephant and (b) African Forest Elephant (b)**.** Data were simulated from a log-normal distribution parameterized using the full posterior of model parameters. Medians of the simulated data are plotted against observed values and shown to be a close match.

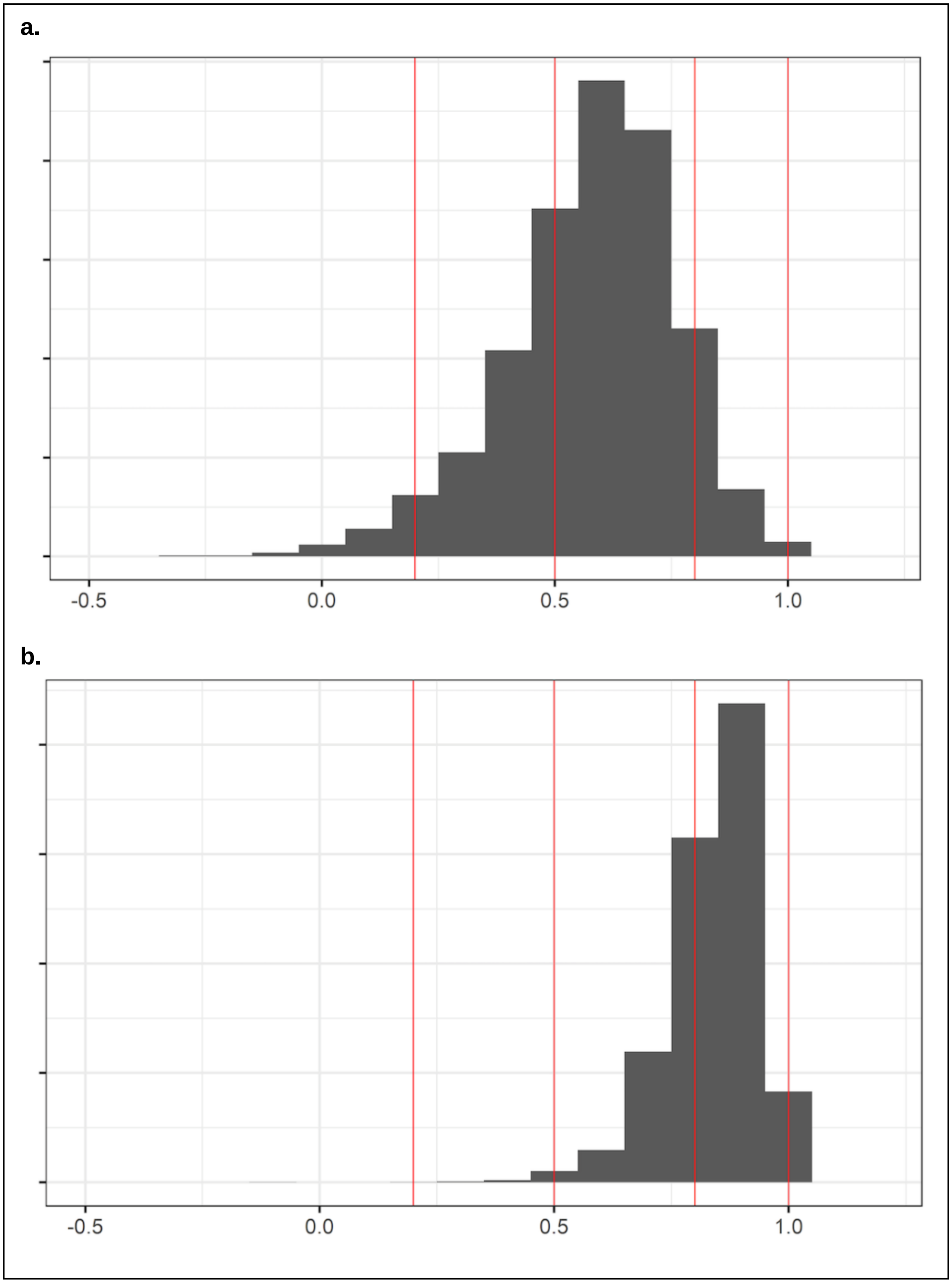

Figure 2. Posterior distribution of expected population reduction of the global population of (a) African Savanna Elephant and (b) African Forest Elephant. The x-axis represents

population reduction and the y-axis depicts probability (i.e., number of runs out of total model runs). The boundaries between IUCN Red List Categories are shown by red lines.

Bibliography

For any references cited, see the Bibliography section in the Red List assessments for their details.