Quantifying Biodiversity Impact

Relations amongst local and global metrics, why they matter, and how to offset impacts

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by

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List of Symbols

Symbol	Meaning	Defined in
BSC	Biodiversity Stewardship Credits	Eq. (4.3)
C_i	Index set of lattice elements covering the range of species i	Sec. 3.3
$\lvert C_i \rvert$	Number of lattice elements covering the range of species i	Sec. 3.3
E	Number of lattice element covering Earth	Sec. 3.2
e	Index of a lattice element	Sec. 3.2
ED	Environmental damage from life-cycle impact assessments	Sec. 4.1
$\exp(\quad)$	Exponential function	
i	Index of a species	Sec. 2.1
$\mathcal{L}$	Sum of logarithmic abundances	Eq. (2.1)
$\mathcal{L}_{\text{reg}}$	Measures long-term species survival probability	Eq. (2.3)
$\log(\quad)$	Natural logarithm	
LPI	Living Planet Index	Eq. (2.2)
N_i	Abundance of species i	Sec. 2.1
N_i^*	The abundance of species i at which demographic and environmental stochasticity are of equal size	Sec. 2.3
PDF_e	Potentially Disappeared Fraction of species at e	Sec. 3.6
RSR_e	Range Size Rarity at e	Eq. (3.9)
$\text{STAR}_{t,e}$	Species Threat Abatement and Recovery metric for treat t at e	Eq. (3.9)
S	Number of species in group considered	Sec. 2.1
SD, SD_e	Species density (at e)	Sec. 3.7
$x_{i,e}$	Indicator (1 or 0) for extirpation of species i at e	Sec. 3.3
Δ	Change in the value of a quantity	
ΔA	Size of area covered by one lattice element	Sec. 3.2
ρ_i	Population density of species i	Sec. 3.3

Executive Summary

Headline messages

Quantitative disclosure of biodiversity impacts carries two major risks to businesses and financial institutions:

- Disclosure of impacts in terms of metrics that do not align with the needs of investors, customers and/or the general public and do not measure progress towards policy objectives. This might render the disclosure useless or even lead to accusations of 'greenwashing', despite best intentions.
- Loss of legal or public licence to operate because disclosed total biodiversity impacts are negative and no remedy to offset them is available.

This report suggests solutions to mitigating both risks.

The high current rate of species extinctions is a widely felt major concern. Metrics quantifying changes in extinction risk are therefore likely to align with the needs of ESG investors, customers, and the general public. The report shows that biodiversity impact accounting based on the PDF metric (Potentially Disappeared Fraction of species) addresses this concern. It approximately quantifies changes in the mean long-term probability of global species extinction.

Furthermore, the report shows how one can offset these impacts in the same currency, e.g., by focused measures that reduce the risk of extinction of one or several high-risk species. A market for such offsets would lead to near-optimal allocation of resources to global species conservation.

Main result

The notion of the Potentially Disappeared Fraction (PDF) of species was introduced in the context of life-cycle impact assessments.[1] It was intended as a measure of the local "damage to ecosystems" caused by specific anthropogenic pressures. The term 'disappearance' refers to extirpation in local communities. To compute the global impact of specific pressures, the PDF is multiplied by the average local species density of a region (or mean global species density for simplicity) and then integrated over the surface area of Earth (typically differentiated by land, freshwater, and marine surface). The result is in units of 'species', but not meant as an estimate of the actual species loss resulting from a pressure.

As shown in this report, PDF-base impact metrics do however quantify approximate impacts on one of the most influential measures of global biodiversity status: the Living Planet Index[2] (LPI). The LPI, in turn, has recently been shown to be a measure of mean long-term global species extinctions probability.[3] Specifically, if S is the global number of species in the taxonomic or functional group considered, ED the time integrated PDF-based environmental life-cycle impact of one unit of a product (units: species$\times$year), as computed, e.g., using `ReCiPe 2016`,[4] and r the rate of production of this production (units: $1/$year), then the impact of this production on the LPI is approximately

$$\Delta\mathrm{LPI} \approx -\mathrm{LPI}\,\frac{\mathrm{ED}\,r}{S}. \tag{1}$$

Rewritten in more memorable form, this becomes

$$\frac{\Delta\mathrm{LPI}}{\mathrm{LPI}}\,S \approx -(\text{nominal PDF-based species loss}) \qquad (\text{global life-cycle impact}). \tag{2}$$

Significance for biodiversity impact disclosure

This interpretation of PDF-based metrics is significant in the context of biodiversity impact disclosures by organisations because:

1. Organisations can report mitigation of impacts in terms of PDF as contributions to halting and reversing global biodiversity loss as quantified by the LPI.
2. The derivation of Equation (1) points to opportunities to improve PDF-based impact metrics as better data becomes available.

3. This new interpretation of PDF-base impact metrics permits organisations to adopt—and report on—local measures that compensate the diffuse impact their operation has on biodiversity (as measured by LPI), thus making their operation net biodiversity neutral or even net positive.

An organisation can achieve net positive impacts in terms of LPI, e.g., by adopting measures that change the sustained abundances of the species on the land it holds by ΔN_i (where i numbers species) and the resulting change in LPI, estimated as

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}} S \approx \sum_i \frac{\Delta N_i}{N_i} \qquad \text{(local mitigation impact)}, \tag{3}$$

over-compensates the diffuse global impacts of its operation by Equation (2). In the expression above, N_i denotes the global abundance of species i.[i] By rebuilding populations of species close to extinction (small N_i), large positive offsets can therefore be achieved.

LPI-derived impact metrics as efficient decision support tools

The report demonstrates how several other biodiversity impact metrics can be understood as approximate measures of change in LPI. They measure impact in the same currency but are applicable in different contexts. Equation (2), for example, makes use of approximations valid for diffuse impacts spread over global scales, while Equation (3) is more adequate and rather easily evaluated on small spatial scales.

A third approximation derived in this report is valid at intermediate scales. It makes use of the Range-Size Rarity metric,[5] which conservation ecologists use to make decisions on the placement of nature reserves. The LPI-derived impact metrics discussed here are therefore aligned with the practice of conservation ecology. The STAR metric,[6] supported by the IUCN, is a variant of Range-Size Rarity.

Common to this family of LPI-derived impact metrics is that, as illustrated in the discussion of offsetting above, they naturally direct conservation efforts to high-risk species—a desirable property for metrics aimed at species conservation. Full marketisation of the metrics would lead to near-optimal allocation of resources to species conservation in terms of LPI.[3]

This report thus provides a coherent, unified perspective on a range of biodiversity metrics for use in the business&finance context. It is hoped to clarify some of the confusion felt about metrics and to contribute to their effective use.

[i] For species close to the extinction threshold a regularisation of LPI is required, which leads to a correction in Equation (3).[3]

1 Introduction

The need for generic metrics of the biodiversity impact of organisations and their activities is widely accepted. The fact that there is no single metric that addresses all requirements should not prevent the search for suitable science-based metrics that are widely applicable, directly speak to the needs of investors, customers and/or the general public, and send the right market signals to attain the objectives they are designed to achieve.

Species are currently disappearing from Earth at a rate so high that it has been likened to mass extinctions engraved in the geological record.[7] Extinctions of species are a major public concern.[8] On this background, this report addresses the objective of reducing the rate of global species extinctions. It is written with the conviction that, in order to be truly "science based", a metric's methodology should not only employ methods used in scientific research. There should also be scientific demonstration that the metric is suitable for achieving the high-level objective it is meant to address. This requires careful quantitative reasoning, reflected in the lush use of mathematical notation in this report.

Mathematical arguments reveal dependencies and relations between different biodiversity metrics and indices, thus helping to reduce the confusion felt across business, finance, and conservation communities about the multitude of proposed metrics.

A metric frequently used in biodiversity impact assessment tools for businesses and financial organisations is the 'Potentially Disappeared Fraction' of species (PDF).[1] It quantifies the proportion of species locally going extinct in response to external pressures and is typically determined through ecotoxicological experiments. The metric underlies, e.g. the BFFI (Biodiversity Footprint for Financial Institutions[ii]), PBF (Product Biodiversity Footprint[iii]) and a well-established family of tools developed for product life-cycle impact assessments.

This report shows how PDF-based impact metrics can be linked mathematically to the Living Planet Index[2] (LPI). This is interesting in its own right, since LPI is a widely cited metric of global biodiversity status. Based on the recent observation that changes in LPI quantify changes in mean long-term species survival probability,[3] it also leads to an interpretation of PDF-based impact metrics in terms of impacts on global extinction risk. Through the link to LPI, PDF-based metrics also become comparable to other LPI-derived impact metrics, obtained by invoking approximations valid in particular contexts. These express impacts in the same currency as PDF-based metrics and can so be combined, e.g. in order to demonstrate offsetting of the diffuse biodiversity impacts of business operation.

In view of the central role the LPI plays in this analysis, Chapter 2 explains this metric in some detail. Chapter 3 derives several approaches to estimating approximate impacts on LPI, thus establishing linkages between PDF, LPI, Range Size Rarity, STAR[6] and global species richness. Chapter 4 briefly discusses offsetting strategies.

[ii] https://www.government.nl/documents/reports/2021/07/29/biodiversity-footprint-for-financial-institutions

[iii] http://www.productbiodiversityfootprint.com/

2

The Living Planet Index

The global Living Planet Index (LPI) is designed to track average "species population trends"[2] for a given taxonomic or functional group of species (hereafter "group of species" or similar). In defining the LPI, one needs to distinguish the quantity it aims to represent conceptually and how it is being computed in practice.

2.1. Definition

Conceptually, LPI is the geometric mean[iv] of the global abundances of all species in the group considered, normalised to a fixed baseline year.

> LPI measures changes in geometric mean abundance of species.

Mathematically, if S is the total number of species in the group and N_i the global population size of the i-th species in this group, one can compute the sum of the natural logarithms (symbol: log) of population sizes as

$$\mathcal{L} = \sum_{i}^{S} \log N_i, \tag{2.1}$$

and from this

$$\mathrm{LPI} = \exp\left(\frac{\mathcal{L} - \mathcal{L}_0}{S}\right), \tag{2.2}$$

where $\mathcal{L}_0$ is the value of $\mathcal{L}$ in the baseline year.

2.2. Computation

The global LPI for vertebrate species is regularly published by the WWF.[2] The baseline year is 1970. Its value is estimated from a large database of population time series using a methodology developed by the Zoological Society of London.[9] The methodology compensates for incomplete and uneven temporal, taxonomic and geographic coverage of the database. It also takes into account that many times series in the database refer to local or regional rather than global populations.

To address the last issue, the methodology estimates the trend in the global abundance of a recorded species as the trend in the geometric mean of all population time series available for that species. One therefore might argue that the published LPI does not actually estimate changes in the geometric mean of global population sizes, but the geometric mean of the sizes of local populations, which is different, especially in cases of local species extinctions.[v] However, if one changes the methodology to use a more appropriate

[iv] The geometric mean of N numbers $x_1, \ldots, x_N$ is defined as $\sqrt[n]{x_1 \cdot \ldots \cdot x_N}$.

[v] Let the global population of a species be given by the sum of two local sub-populations, n_1 and n_2. Assume that $n_1 = 100$ and $n_2 = 100$ in 1980, while $n_1 = 100$ and $n_2 = 0$ in 1990. Then geometric mean local population size has declined from 100 to 0 during this decade. As an estimate of global population trend, this would imply species extinction. In fact, the species' global population declined only by a factor $1/2$.

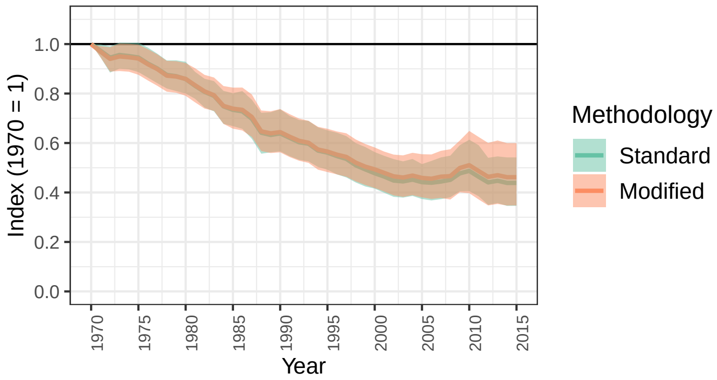

Figure 2.1: Comparison of the global Living Planet Index for two methods to estimate global abundances trends of species from limited local abundance data. Shaded areas indicate confidence intervals. The 'Standard' method represents the global abundance trends by the trend of the geometric mean of local abundances, the 'Modified' method estimates the trend from the sum of the available local population time series. To account for ignorance about the absolute population sizes that time series effectively represent, all time series are standardised to attain the same maximum value.

method to estimate global abundance trends of species from the limited available data, the resulting estimate of global LPI changes only little (Fig. 2.1). One can therefore safely interpret the published global LPI as estimating trends in global population sizes of species, as given by Equations (2.1) and (2.2). The analysis here relies on this interpretation.

2.3. Regularisation and interpretation as measure of extinction risk

Since the LPI is proportional to the geometric mean of the population sizes of all species S in the group of interest, it follows that LPI $= 0$ after one of those species went extinct. In Equation (2.1) this would be reflected by $\mathcal{L}$ attaining a value of negative infinity (because $\log(x) \to -\infty$ as $x \to 0^+$), which leads to a value of zero for LPI by Equation (2.2).

The methodology for practical computation of the LPI circumvents this problem by invoking heuristic rules when local population sizes approach zero.[9,10]

To overcome this problem on a conceptual level, define

$$\mathcal{L}_{\mathrm{reg}} = \sum_{i}^{S} \log\left(1 + N_i/N_i^*\right), \tag{2.3}$$

with N_i^* denoting the population size of species i at which demographic and environmental stochasticity[11] contribute equally to long-term population fluctuations (typical values for N_i^* are of the order of 100 individuals[11]).

$\mathcal{L}_{\mathrm{reg}}$ is proportional to the expected number of species still extant after a long time.

The quantity $\mathcal{L}_{\mathrm{reg}}$ has particular significance in the context of species conservation: it can be shown that, under some simplifying assumptions, $\mathcal{L}_{\mathrm{reg}}$ is proportional to the expected number of species still extant after a long time.[3] The proportionality constant depends on the time horizon considered and other parameters of the underlying model.

In addition, $\mathcal{L}_{\mathrm{reg}}$ does not suffer from the singularities arising for $\mathcal{L}$, Equation (2.1), in the case of extinctions. If one of the S species in Equation (2.3) goes extinct ($N_i = 0$), the corresponding term in the sum becomes zero rather than negative infinity. Intrinsically consistent, an extinct species hence has the same effect as a non-existent species. One the other hand, when all populations sizes N_i are much larger then the corresponding constants N_i^*, the values of $\mathcal{L}_{\mathrm{reg}}$ and $\mathcal{L}$ differ only by some additive constant.[vi] In this case, a regularisation of LPI by replacing $\mathcal{L}$ by $\mathcal{L}_{\mathrm{reg}}$ in the definition of LPI, Equation (2.2), does not change its value. When species do go extinct, however, the regularised LPI provides informative, non-zero values.

[vi] For $N_i \ll N_i^*$ one can approximate $\log(1 + N_i/N_i^*) \approx \log(N_i/N_i^*) = \log(N_i) - \log(N_i^*)$. Hence $\mathcal{L}_{\mathrm{reg}} \approx \mathcal{L} - \sum_i \log(N_i^*)$ in this approximation.

Importantly, by the role of $\mathcal{L}_{\text{reg}}$ as a predictor of survival probability, the regularisation of LPI by using $\mathcal{L}$ in place of $\mathcal{L}_{\text{reg}}$ makes LPI itself a predictor of the expected long-term survival of species and so a suitable metric for a risk-based approach to biodiversity.

Changes in LPI quantify changes in mean long-term species survival probability.

In most practical cases, populations N_i are sufficiently large compared to N_i^* that the effect of regularisation is negligible. To the degree that this is the case, the conventional LPI is a predictor of long-term species survival probability just as the regularised variant is.

In the following calculations, the conventional definition of LPI in terms of geometric mean abundance via Equations (2.1) and (2.2) shall therefore be used for simplicity. It is worth keeping in mind, though, that singularities arising in derived formulas for small population sizes can always be avoided by transitioning from $\mathcal{L}$ to $\mathcal{L}_{\text{reg}}$, at the price of slightly more complicated mathematical expressions.

Since in subsequent considerations management of long-term extinction risk is the primary concern rather than the management of the LPI, the question whether for a particular group of species an LPI time series has already been published or not is not immediately relevant. Considerations regarding extinction risk are valid regardless.

3

Estimating Impacts on the Living Planet Index

The following discusses how to calculate anthropogenic impacts on the LPI in terms of other established metrics, including PDF. The discussion proceeds in several steps, with each step corresponding to the introduction of a new approximation in the calculations.

3.1. The approximation of small impacts

The value of LPI changes as the populations of the species it represents change. When these changes are small, one can approximate the impact on LPI to linear order as

$$\Delta \mathrm{LPI} \approx \sum_{i}^{S} \frac{\partial \mathrm{LPI}}{\partial N_i} \Delta N_i, \tag{3.1}$$

with $\partial/\partial N_i$ denoting partial derivatives and ΔN_i the amount by which the global population of species i changes.

From Equations (2.1), (2.2) and (3.1) one obtains by textbook calculus,

$$\Delta \mathrm{LPI} \approx \sum_{i}^{S} \frac{\mathrm{dLPI}}{\mathrm{d}\mathcal{L}} \frac{\partial \mathcal{L}}{\partial N_i} \Delta N_i = \sum_{i}^{S} \exp\left(\frac{\mathcal{L} - \mathcal{L}_0}{S}\right) \frac{1}{S} \frac{1}{N_i} \Delta N_i = \frac{\mathrm{LPI}}{S} \sum_{i}^{S} \frac{\Delta N_i}{N_i}. \tag{3.2}$$

Rearrangement of terms leads to

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}} S \approx \sum_{i}^{S} \frac{\Delta N_i}{N_i}. \tag{3.3}$$

The emphasis in the following will be on right-hand-side of this Equation (3.3).

3.2. Rasterization of Earths' surface

Cover Earths' surface by a lattice of E non-overlapping surface elements of equal area ΔA and, to the degree possible, approximate square shape. Denote by $n_{i,s}$ the number of individuals of species i in lattice element e and by $\Delta n_{i,s}$ changes in these numbers. Summing over all lattice elements, $N_i = \sum_e^E n_{i,e}$. Equation (3.3) can then be written as

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}} S \approx \sum_{i}^{S} \frac{\sum_e^E \Delta n_{i,e}}{N_i} = \sum_{e}^{E} \sum_{i}^{S} \frac{\Delta n_{i,e}}{N_i}. \tag{3.4}$$

It is worth noting that in Equation (3.4) the sum

$$\sum_{i}^{S} \frac{\Delta n_{i,e}}{N_i} \tag{3.5}$$

can be interpreted as describing the local density of impact at lattice element e in units of $1/\Delta A$. The sum over e adds these local impacts up to determine the global impact. To account for the fact that impacts do not necessarily respect lattice boundaries one might rather write Equation (3.4), using a spatially continuous measure of impact density, in a form such as

$$\text{(global impact)} = \iint_{\text{Earth's surface}} \text{(impact density)}\ \mathrm{d}A. \tag{3.6}$$

However, to align with the practice of conservation ecology, the present analysis sticks with a discretization of space as in Equation (3.4).

3.3. The approximation of constant population density

For practical reasons, conservation ecologists often work with presence/absence data of species at lattice elements. Population density is disregarded. To emulate this approach here, assume that each species i has, wherever it is present, a constant density ρ_i. That is, either $n_{i,e} = \rho_i \Delta A$ or $n_{i,e} = 0$.

Denote by C_i the index set of those lattice elements where $n_{i,e} > 0$ and by $|C_i|$ the number of elements of this set. Then $N_i = \rho_i |C_i| \Delta A$ in this approximation.

Let $x_{i,e} = 1$ if the some impact leads to extirpation of species i in element e and $x_{i,e} = 0$ otherwise, so that $\Delta n_{i,e} = -\rho_i x_{i,e} \Delta A$. The possibility of colonisation of new lattice elements by species is disregarded. Validity of the linearization of changes in LPI in Equation (3.1) requires that $x_{i,e} = 0$ for most occupied lattice elements. Under these simplifying assumptions Equation (3.4) can be written as

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}} S \approx -\sum_e^E \sum_i^S \frac{\rho_i x_{i,e} \Delta A}{\rho_i |C_i| \Delta A} = -\sum_e^E \sum_i^S \frac{x_{i,e}}{|C_i|}. \tag{3.7}$$

The crucial observation at this step is that each species' density ρ_i and the size of lattice elements ΔA cancel out.

3.4. The approximation of total destruction

Equation (3.7) can be a good method to estimate biodiversity impact if range maps for the impacted species are available and $x_{i,e}$ is predictable, for example because most species will be extirpated at the impacted lattice elements.

In the approximation that all species (of the group of interest) will get extirpated at impacted lattice elements,

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}} S \approx -\sum_{e \in \mathcal{I}} \sum_{\substack{i \\ e \in C_i}} \frac{1}{|C_i|} = -\sum_{e \in \mathcal{I}} \mathrm{RSR}_e, \tag{3.8}$$

where $\mathcal{I}$ denotes the index set of impacted sites, the notation $e \in C_i$ means a restriction of the sum over i to those species i that are present at e (i.e. e is within their range), and

$$\mathrm{RSR}_e = \sum_{\substack{i \\ e \in C_i}} \frac{1}{|C_i|} \tag{3.9}$$

defines the metric known as Range-Size Rarity.[5]

The Range-Size Rarity metric and variants thereof[12] are often considered in conservation ecology, especially in the selection of protected areas for species conservation. In the simplest case, one would place protected areas in the subset of lattice elements with the highest Range-Size Rarity, with the size of this subset depending on conservation effort.

> Protection of high Range-Size Rarity areas minimises long-term extinction risk.

Above calculation shows that this practice minimises, within a specific approximation, the potential impact on the LPI by total destruction of randomly selected unprotected sites. By the interpretation of the LPI as a predictor of species survival, this implies that selection of protected areas based on Range-Size Rarity is the strategy that minimises long-term global species extinction risks if range maps are the only data available. This result substantiates intuitive arguments conservation ecologists have invoked since 1991 to justify use of Range-Size Rarity in conservation decisions.[13]

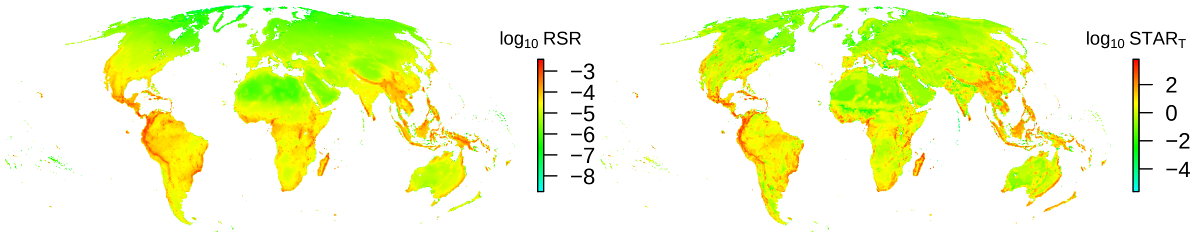

Figure 3.1: Comparison of Range-Size Rarity (RSR) and Species Threat Abatement and Recovery ($\mathrm{STAR_T}$) metrics for amphibians, birds and mammals. Spearman's rank correlation of the two global data sets is 0.80. Logarithmic major axis regression yields $\mathrm{STAR}_{\mathrm{T},e} \propto (\mathrm{RSR}_e)^{1.51}$. The $\mathrm{STAR_T}$ data was published in Ref. 6, the RSR data was provided by IUCN (`https://www.iucnredlist.org/resources/other-spatial-downloads`).

3.5. STAR as a variant of Range-Size Rarity

The Species Threat Abatement and Recovery (STAR) metric[6] is a weighted variant of Range-Size Rarity. The threat-related STAR (summed over all threats), for example, is given by

$$\mathrm{STAR}_{\mathrm{T},e} = \sum_{\substack{i \\ e\in C_i}} \frac{W_i}{|C_i|}, \tag{3.10}$$

with the weighing factors W_i quantifying the IUCN Red-List category of species i by an integer ranging from 0 (Least Concern) to 4 (Critically Endangered).

STAR and Range-Size Rarity are closely related metrics.

In a sense, $\mathrm{STAR_T}$ contains information on threat level twice. In the form of range size $|C_i|$ and through the weights W_i. Indeed, W_i and logarithmic range size are strongly correlated[vii]. Because $|C_i|$-values vary over many orders of magnitude, most of the variation in $\mathrm{STAR_T}$ is due to $|C_i|$ rather than W_i. As a result, the global patterns of variation of $\mathrm{STAR}_{\mathrm{T},e}$ and RSR are very similar (Fig. 3.1).

3.6. The approximation of random extirpations

Instead of localised total destruction one can also consider the case of wide-spread small impacts. This is the kind of problem typically considered in life-cycle assessments. In this context, the concept of the *potentially disappeared fraction* of species (PDF) has been introduced to quantify diffuse impacts of products on the environment.[1] The metric is defined as the proportion of locally extant species that get extirpated (i.e. 'disappear') as a result of exposure to a pressure such as environmental pollution. The 'disappearance' of species quantified by PDF is considered reversible once the pressure has ceased.

Denote by PDF_e the potentially disappeared fraction of species at site e. Now, recall that if a species i locally disappears (i.e. is extirpated), then $x_{i,e}$ in Equation (3.7) is one, and otherwise it is zero. If the probability that a species i extant at some site e is amongst the fraction that locally 'disappears' at this site is statistically independent of its range size $|C_i|$, one therefore obtains from Equation (3.7)

$$\frac{\Delta\mathrm{LPI}}{\mathrm{LPI}} S \approx -\sum_e^E \sum_i^S \frac{x_{i,e}}{|C_i|} \approx -\sum_e^E \sum_{\substack{i \\ e\in C_i}} \frac{\mathrm{PDF}_e}{|C_i|} = -\sum_e^E \left(\sum_{\substack{i \\ e\in C_i}} \frac{1}{|C_i|} \right) \mathrm{PDF}_e = -\sum_e^E \mathrm{RSR}_e \, \mathrm{PDF}_e \tag{3.11}$$

on average.

Equation (3.11) nicely summarises relations between various status and impact metrics used in the study and conservation of biodiversity: LPI, RSR, PDF and global species richness S.

$\Delta\mathrm{LPI}\, S \approx -\mathrm{LPI} \sum_e^E \mathrm{RSR}_e\, \mathrm{PDF}_e$

[vii] See Extended Data Figure 4b in the original publication.[6]

3.7. The approximation of Range-Size Rarity by species density

Range-Size Rarity is closely related to species density. To see this, consider the sum of RSR_e over an area that is much larger than the typical range of a species, such that the range of each species is to a good approximation either entirely within this area or entirely outside of it.

The S species i in the group considered can then be divided into two sets: those not contained in the area considered and those that are. The former are excluded from the sum $\sum_{i,\, e\in C_i} |C_i|^{-1}$ defining RSR_e for any lattice element e in the area considered. Species of the latter type contribute to RSR_e at $|C_i|$ different elements e within the area, each time by $1/|C_i|$, such that the total contribution of each such species to the sum of RSR_e over the area is 1. The sum of RSR_e over the area therefore equals the number of species in this area. It follows that, when averaged over large spatial scales, RSR_e equals species density (i.e. the number of unique species per unit area) in units of the inverse size of a lattice element $1/\Delta A$.

On large spatial scales species density is easier to determine than Range-Size Rarity, as it does not require detailed information on species ranges. With SD_e denoting an estimate of species density for lattice element e, one can therefore usefully approximate Equation (3.11) further as

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}}\, S \approx -\sum_{e}^{E} \mathrm{SD}_e\, \mathrm{PDF}_e. \tag{3.12}$$

3.8. The approximation of constant species density

If one assumes that species density has, for the group of species considered and at those locations e where $\mathrm{PDF}_e > 0$, a fixed value SD (in units of $1/\Delta A$), then Equation (3.11) simplifies further to

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}}\, S \approx -\mathrm{SD} \sum_{e}^{E} \mathrm{PDF}_e. \tag{3.13}$$

The right-hand-side of Equation (3.13) is of a form typical for environmental life-cycle impact assessments. Its conventional interpretation as a measure of integral ecosystem impact is, similarly to the case of Range-Size Rarity, ultimately rooted in heuristic arguments. By the mathematical analysis here, the expression on the right-hand-side of Equation (3.13) can be understood as a measure of impact on LPI, and, since LPI quantifies long-term species survival, as a measure of impact on long-term species survival.

If one writes the species density in Equation (3.13) as $\mathrm{SD} = S/E$, recalling that S denotes global species richness and E the total number of lattice elements covering Earth's surface, Equation (3.13) becomes

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}}\, S \approx -\frac{S}{E} \sum_{e}^{E} \mathrm{PDF}_e = -S\, \frac{\sum_e^E \mathrm{PDF}_e}{E} = -S\, \overline{\mathrm{PDF}}, \tag{3.14}$$

with $\overline{\mathrm{PDF}}$ denoting the global average of PDF, the probability of local species extirpation. Cancelling S on both sides leads to the compact result

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}} \approx -\overline{\mathrm{PDF}} \tag{3.15}$$

for the relation between PDF and LPI.

3.9. What PDF predicts about global extinction risk

The considerations above establish a relationship between local extirpations and global extinctions. The relation is, however, not as simple as one might naively expect. In Equation (3.14), for example, the product of species number and probability of extirpation can be read as a nominal predicted species loss. An interpretation as an actual prediction of global species loss, however, would be incorrect.

To establish the specific link to global extinctions, note that, in the linear approximation invoked throughout this chapter, the left-hand-side of Equation (3.13) can be re-written as

$$\frac{\Delta \mathrm{LPI}}{\mathrm{LPI}}\, S = \frac{S}{\mathrm{LPI}} \frac{\mathrm{dLPI}}{\mathrm{d}\mathcal{L}} \Delta\mathcal{L} = \frac{S}{\mathrm{LPI}} \exp\left(\frac{\mathcal{L} - \mathcal{L}_0}{S}\right) \frac{1}{S}\, \Delta\mathcal{L} = \Delta\mathcal{L} \approx \Delta\mathcal{L}_{\mathrm{reg}}, \tag{3.16}$$

with $\Delta\mathcal{L}$ denoting the small change in $\mathcal{L}$ corresponding to the small change $\Delta\mathrm{LPI}$ in LPI, and $\Delta\mathcal{L}_{\mathrm{reg}}$ the corresponding change in $\mathcal{L}_{\mathrm{reg}}$. The last step follows because $\mathcal{L}$ and $\mathcal{L}_{\mathrm{reg}}$ typically differ only by an additive constant.

Since $\mathcal{L}_{\text{reg}}$ is proportional to the expected number of species surviving after a long time, the quantity given by Equation (3.14) is, by Equation (3.16), proportional to the change in the expected number of species that are still extant after a long time. As explained above the proportionality constant depends on the time horizon considered and other parameters.

Figure 3.2 summarises the approximations involved in establishing this and other relations discussed in this report.

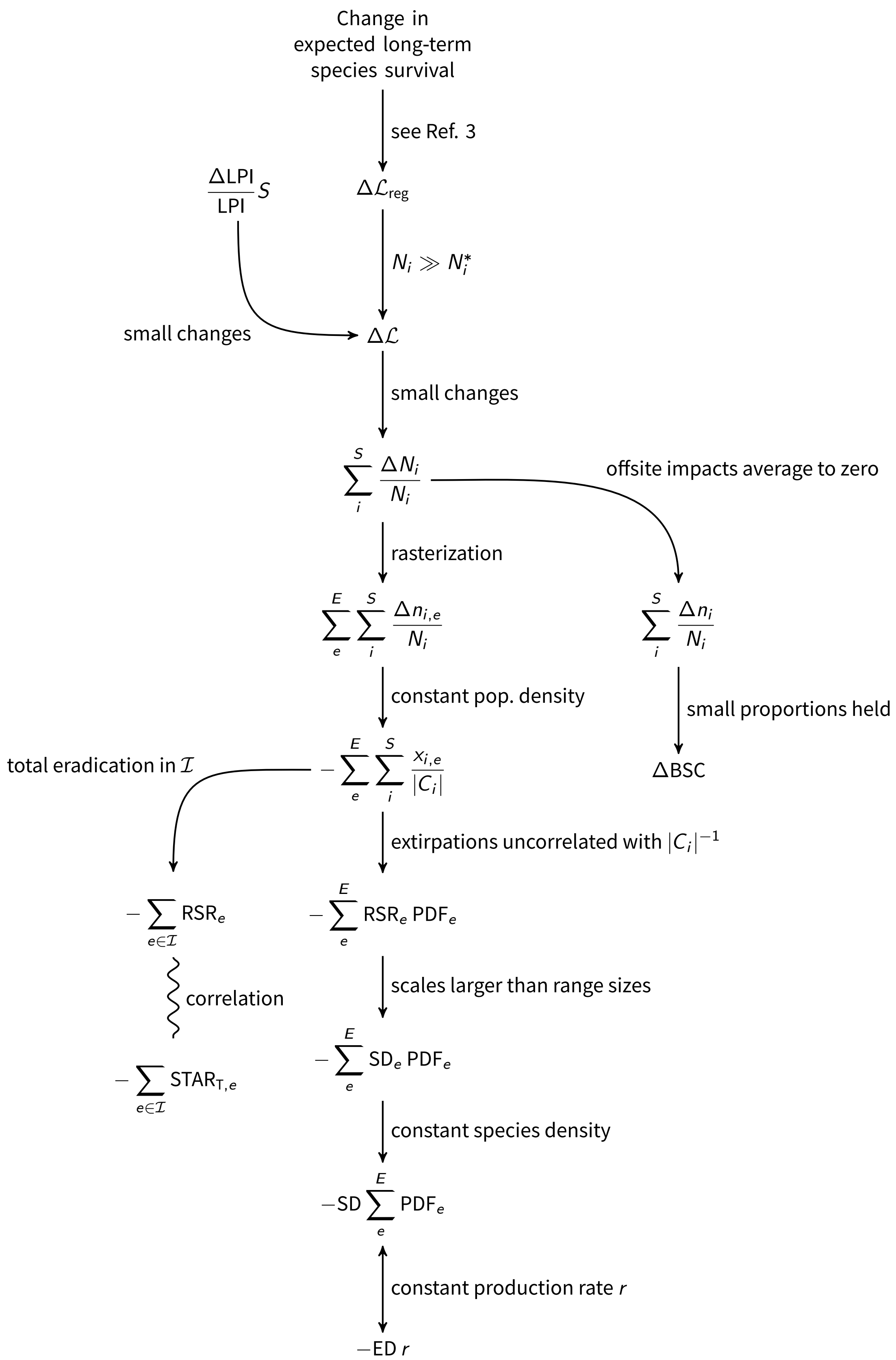

Figure 3.2: Approximations underlying the relations discussed in this report. Annotations of arrows indicate the underlying simplifying assumptions. Where these assumptions are inadequate corresponding approximations can be omitted.

4

Offsetting Impacts on the Living Planet Index

This chapter briefly discusses strategies and consideration for offsetting biodiversity impacts quantified in terms of the associated changes in the LPI.

4.1. From PDF-based life-cycle impact assessment to global biodiversity impacts

It is common practice in life-cycle impact assessments to first consider several midpoint level effects of a product (e.g. different forms of environmental pollution) and to then sum up these effects in a common currency, which is given by the impact that the midpoint level effects have on the endpoint of interest. The environment is thought to eventually recover from the midpoint-level effect of one unit of product, leading to a corresponding recovery of the endpoint. Life-cycle assessments therefore report the time-integrated effect of a product at the endpoint level over the duration of the effect. As a result of this integration, units of impact generally contain a factor 'year'.

The tool `ReCiPe 2016`,[4] for example, output a measure of damage to terrestrial and freshwater ecosystems in units of species × year, where the factor 'species' derives from calculations analogous to the right-hand-side of Equation (3.13) and the factor 'year' from the time integration. When multiplying this measure of ecosystem damage (ED) by the rate r of production of the product, one obtains an estimate of the static effect of continuous production. Alternatively, one could compute static midpoint and endpoint effects resulting from a given continuous rate of production directly and obtain the resulting global impacts as in Equation (3.13).

> Nominal PDF-based species loss correlates with change in global extinction risk.

Thus, conceptually,

$$\text{(change in mean extinction risk)} \propto -\frac{\Delta\text{LPI}}{\text{LPI}}\, S \approx \text{SD} \sum_{e}^{E} \text{PDF}_e = \text{ED}\, r = \text{(nominal PDF-based species loss)}. \tag{4.1}$$

This deeper understanding of the ecosystem impact measures generated by life-cycle impact assessments points to avenues for effective, demonstrable offsetting.

4.2. The approximation of local impacts

To compute the effects on global LPI of pronounced, localised impacts by an organisation resultig from business operation or conservation measures, use of the direct estimate in Equation (3.3) is advised.

It can be simplified further by disregarding indirect ecological effects of these impacts outside the area controlled by the organisation. Such long-range effects, caused by migration and dispersal of individuals, exist, but simulations suggest that their mean effect on global population sizes is close to zero.[14]

Denote by n_i the abundance of species i within the area controlled by the organisation. Then Equation (3.3) simplifies further to

$$\frac{\Delta \text{LPI}}{\text{LPI}} S \approx \sum_i^S \frac{\Delta n_i}{N_i}, \tag{4.2}$$

with Δn_i denoting changes in n_i. Because global population sizes N_i vary over many orders of magnitude, the sum on the right-hand-side of Equation (4.2) will often be dominated by just a handful of species. When the area controlled by the organisation contains one or a few particularly rare species, changes in their abundance can make large contributions to the sum that entirely dominate it.

Targeted conservation measures can offset diffuse impacts on LPI.

Consequently, measures to protect and enhance the populations of rare species can generate substantial increases in LPI. Organisations aiming to offset diffuse negative impacts on LPI resulting from their operation can therefore engage in the rebuilding of populations of rare species to offset these impacts. Alternatively, they may partner with other organisations that provide the offsetting as a service.

4.3. From a planned to a dynamic economy of biodiversity

Biodiversity offsetting schemes based on restoration measures must consider the real risk that anticipated biodiversity gains do not materialise. This risk can be addressed by making its management an economic activity rather than part of the planning and forecasting involved in computing predicted biodiversity gains.

Define the Biodiversity Stewardship Credits[3] held by an organisation as[viii]

$$\text{BSC} = \sum_i^S \frac{n_i}{N_i}, \tag{4.3}$$

with n_i again denoting the abundance of species i within the area controlled by the organisation. As long as the proportions n_i/N_i held of each species by an organisation are not too large[ix] it follows from Equation (4.2) that

$$\frac{\Delta \text{LPI}}{\text{LPI}} S \approx \Delta \text{BSC}, \tag{4.4}$$

with ΔBSC denoting a change in the BSC held by the organisation.

The crucial difference between Equations (4.2) and (4.4) is conceptual rather than mathematical. Equation (4.4) suggests that an organisation can demonstrate the contributions of its local activities to LPI by comparing measured BSC before and after an intervention (rather than based on projections of population change). These demonstrated credits could then be used to offset diffuse impacts as estimated, e.g., by Equation (4.1). Alternatively, the credits could be acquired from partner organisations. In either case, an organisation can use this scheme to demonstrate an overall biodiversity neutral or positive operation.

It is worth emphasising that, since continuous production at a constant rate leads to a constant change in LPI by Equation (4.1), an organisation needs to build the BSC to offset this change only once and then keep holding the BSC to maintain biodiversity neutrality. When production ceases, the credits can gradually be transferred within or across organisations to offset other forms of operation, at the rate that the environment is expected to recover from impacts. Tools such as `ReCiPe 2016`[4] implicitly or explicitly include models for the dynamics of these recovery processes.

Similarly, the environmental impacts resulting from the production of a product at constant rate gradually build up over time. Correspondingly, the BSC required for offsetting can be built up gradually, leaving time for populations to grow and ecological communities to form naturally on the land held for this purpose.

A crucial characteristic of this scheme is that both the risk of under-performance of BSC restoration projects and the opportunity of gaining transferable surplus BSC in well-managed projects lie with the landholder

[viii] The definition in Ref. 3 includes a regularisation related to the difference between $\mathcal{L}$ and $\mathcal{L}_{\text{reg}}$.

[ix] When $n_i/N_i \ll 1$, proportional changes in N_i resulting from local conservation measures are much smaller than proportional changes in n_i and so can be disregarded when computing changes in BSC.

rather than with an organisation computing anticipated future credits. This creates incentives for fast, efficient and predictable building of BSC and so improved allocation of resources to biodiversity conservation. One can show[3] that an ideal market for BSC would lead to near-optimal allocation of resources to attain a given value of LPI—and so reduce mean long-term extinction probability at minimal cost.

Marketisation of the risks of biodiversity offsetting improves risk management.

Such efficiency gains through marketisation of biodiversity offsets become possible because impacts and offsets are measured in a common, genuinely science-based currency. More restrictive like-for-like offsetting schemes forgo this potential for efficient resource allocation, and so risk diverting scarce resources away from interventions that genuinely reduce the risk of global species extinctions.

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