Bridging the Gap Between Biodiversity Footprint Metrics and Biodiversity State Indicator Metrics

Understanding the purposes and relationships between biodiversity metrics with a special focus on the Living Planet Index and PDF-based footprinting metrics

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Fact-based sustainability

About this document

This whitepaper is based on a much more detailed mathematical and conceptual analysis by Axel Rossberg: Quantifying Biodiversity Impact. We strongly recommend reading this paper if you have the ability to read and understand mathematical formulas, as it provides all the details, assumptions and limitations.

The accompanying paper on which this whitepaper is based can be retrieved via https://www.qmul.ac.uk/sbbs/media/sbbs/research/bsc-project/QMUL-QuantifyingBiodiversityImpact2022.pdf or this QR code.

Quantifying Biodiversity Impact

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

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Queen Mary

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Netherlands & United Kingdom. If further updates of this whitepaper are made these will appear on www.biodiversity-metrics.org

Get in touch with us

Do you have a sustainability challenge for us? We would be happy to discuss it together.

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Executive Summary

Chapter 1: Introduction and high-level messages

We distinguish two perspectives on biodiversity:

1. State Indicator Metrics, which are used by governments and NGOs to support policies and set targets.
2. Footprint Metrics, which are used by companies to assess their impacts.

This paper shows how such metrics can be linked mathematically based on an analysis by Axel Rossberg from Queen Mary University of London. This finding is relevant as it allows companies to report their impacts directly in relation to policy targets.

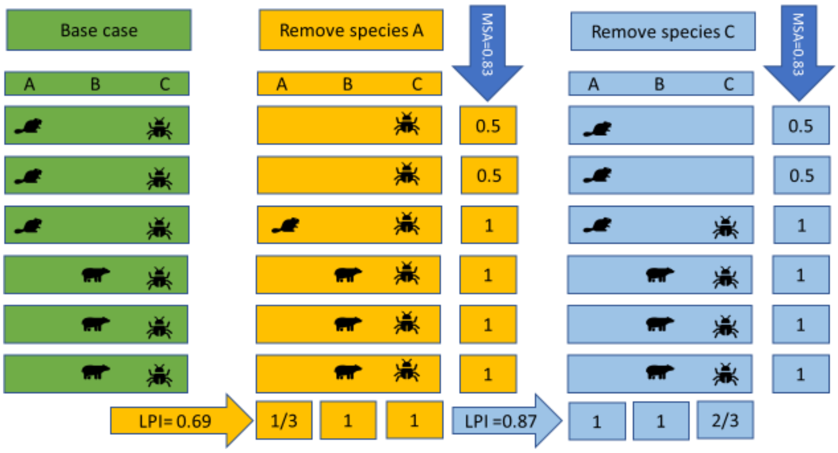
Chapter 2: Understanding State Indicator Metrics

We explain two types of State Indicator Metrics, which are both based on comparing species population sizes in a base year with the current population sizes.

1. The Living Planet Index (LPI) as published by the WWF. This metric is very sensitive to rapid decreases in population density, even if these occur among relatively few species. Its main aim is to monitor changes in extinction risk.

2. Mean species Abundance (MSA), which focusses on the intactness of ecosystems. It is not too sensitive for extinction risks.

The figure below illustrates a case where these metrics have different results for the same situation.



Assume 6 plots with one species A on the first three plots, another species B on the last three and one species C on all plots. This example shows that the LPI is sensitive to the number of plots where a species occurs while the MSA metric is not.

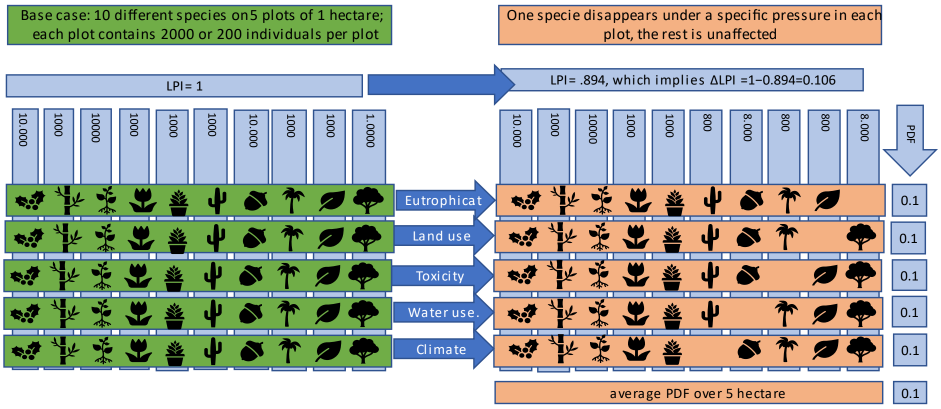
Chapter 3: Footprint Metrics

We describe two Footprint Metrics that are based on cause-effect mechanisms predicting change resulting from environmental pressure, such as climate change, land-use, eutrophication etc.:

1. Potentially Disappeared Fraction of Species (PDF) which predicts the disappearance of species due to an environmental pressure, in a certain area during a certain time. This metric does assume the disappearance is temporary and the species may return if the pressure is mitigated or disappears. This metric has a long track record in life-cycle assessment applications.
2. Mean Species Abundance (MSA). This metric is derived from the State Indicator Metric and has relatively recently been used as a Footprint Metrics. It also links changes in MSA to environmental pressures, and also assumes reversibility in this application.

Chapter 4: Bridging the Gap

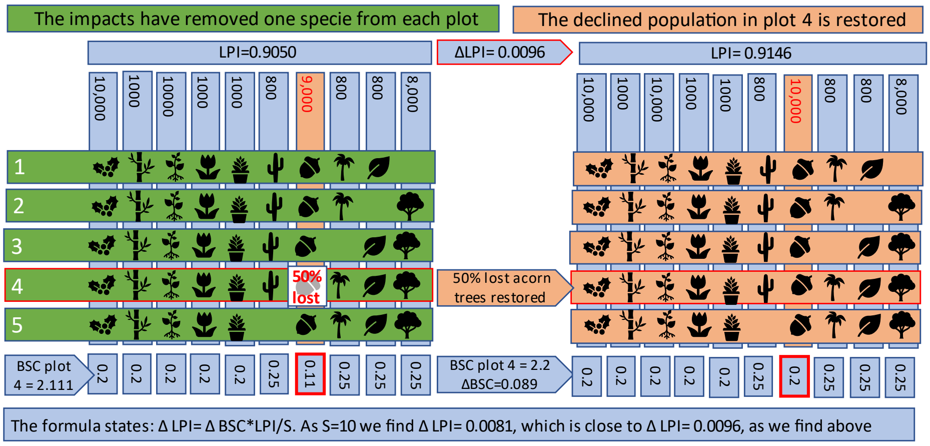
This chapter is the core of the document. We illustrate how Footprint Metrics based on PDF can be directly linked to the Living Planet Index using a toy example. This works under the assumption that the impacts caused by a company are distributed over a wide area, which is a fair assumption as most supply chains are globally spread out. The figure below provides one example that illustrates the relationship. The change in LPI is 10,6%, while the change in PDF = 10%. Not a perfect match, but close.



Example in which 5 plots contain the same species composition and the same number of plants per plot (either 200 or 2000, resulting in a total of 1000 or 10,000). The pressures causes a disappearance of one species in each plot; we assume they are different species

Chapter 5: Compensating impacts: Biodiversity Stewardship Credits

This paper does not advocate the idea that all impacts should be compensated, as the first priority is to reduce impacts. However, there will always be residual impacts from almost any operation, and it is important to understand metrics that can be used to gauge the extent of compensatory measures. An example of a metric that can assess compensatory measures on a more local scale is the Biodiversity Stewardship Credits (BSCs) concept. This concept can be linked to LPI and thus PDF: ΔLPI ≈ ΔBSC * LPI / S. Again, we illustrate the relationship with a toy example:



Example in which 50% of the acorn species loss on Plot 4 is restored by compensating measures, while the other plots are unchanged.

The restoration of the acorn population (from 50% to 100%) leads to an improvement of the LPI of 0.0096. We now test the prediction ΔLPI ≈ ΔBSC * LPI / S= 0.0081. This is rather close to the calculated ΔLPI = 0.0096

Chapter 6: Conclusions

We acknowledge that this paper tries to illustrate the key findings from the original mathematical analysis of Axel Rossberg in extremely simplistic examples. The next step would be to apply these findings in more sophisticated, real-life examples and to develop some case studies.

1 Introduction and high-level messages

Society needs to minimize the risk of species extinctions in the long term. Businesses can contribute to this by considering how their activities affect this risk. IUCN's Red List Index and the Living Planet Index (LPI), published by the WWF, are leading indices for the risk of species extinction at global level[1]. The purpose of these indices is to monitor the "state" of biodiversity and document its ongoing decline. We refer to these as State Indicator Metrics.

Companies cannot directly change the state of global biodiversity, but they can influence it. The metric they use to assess this influence are often referred to as footprintings. So far, the value of a company footprint seemed to have no link to the State Indicators used by policy maker, so whatever a company reports, it could not be linked to national and international State Indicator Metrics. This is unlike the situation around carbon footprinting, as carbon footprints use the same metric that are used, for instance, in the Paris Agreement. As a result, companies can now be linked to a carbon budget or other science-based targets.

This paper explains that existing biodiversity Footprint Metrics can also be directly related to biodiversity State Indicator Metrics, and this opens the possibility to develop equivalent policies around target setting. At first sight, this finding is somewhat surprising as these metrics can be defined very differently. For example, the concept of Potentially Disappeared Fraction of species (PDF), used in biodiversity footprinting, provides a good and relatively easy way to approximate how footprints impacting the LPI State Indicator Metric.

Some metrices are closely associated with dedicated tools to compute them and we will briefly describe these tools if relevant for understanding a metric. The paper covers the following metrics:

- Living Planet Index (LPI)
- The Mean Species Abundance (MSA)
- The IUCN Red List Index
- Potentially Disappeared Fraction (PDF)
- Biodiversity Stewardship Credits (BSC)
- Range Size Rarity (RSR) and STAR, which is linked to the Red List Index

With this paper, we also aim to build a bridge between the communities that use state indicator metrics and those that use Footprint Metrics, as indeed there seems to be little exchange of thoughts between them. For this reason, we summarize how several such metrics work. These summaries are far from complete but try to capture the essence. The purpose is to reduce the level of confusion about tools and metrics quantifying biodiversity impact, with the goal of providing guidance on which tools to use for which purpose. It is addressed to policymakers, businesses, NGOs and all who want to understand the developing landscape of biodiversity impact metrics and tools.

This paper is based on a thorough systematic and mathematical analysis of the relationships between such metrics, developed by Axel Rossberg from Queen Mary University of London, one of the authors of this paper. The original report and a preprint of a more extensive scientific study building on it can be found online[2], but understanding these requires fluency in mathematics. To reach a broader audience, this whitepaper highlights the most important findings in an easier-to-read format with several examples to illustrate the logic.

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[1] Collen, B., Loh, J., Whitmee, S., McRAE, L., Amin, R., Baillie, J.E.M., 2009. Monitoring change in vertebrate abundance: the Living Planet Index. Conservation Biology 23, 317–327. https://doi.org/10.1111/j.1523-1739.2008.01117.x

[2] Report: https://www.qmul.ac.uk/sbbs/media/sbbs/research/bsc-project/QMUL-QuantifyingBiodiversityImpact2022.pdf
Preprint of scientific paper: https://arxiv.org/abs/2111.03867

2 Understanding State Indicator Metrics

Biodiversity has several components. At a minimum, one distinguishes between genetic diversity, diversity of species, and the intactness of ecosystems that permits them to function to the benefit of society. While there exists a clear empirical relation between local species diversity and local ecosystem functioning, the relation between the species diversity component and the ecosystem function component of biodiversity is much weaker on larger spatial scales. With this in mind, it is important to recall that we protect species diversity not only to support ecosystem function and services, but also on moral grounds: for the benefit of future generations or simply because each species has intrinsic value. Indeed, public support to protect biodiversity because ‘we have a responsibility to look after nature’ is stronger than biodiversity protection for the benefit of our health and well-being, production of goods such as food, materials and medicines, for our long-term economic development, or for its role in tackling climate change[3]. This does not deny the importance of biodiversity protection for all the other reasons, most of which require intact ecosystems. What it shows is, however, that a single metric cannot be enough to guide efforts and gauge successes in protecting global biodiversity.

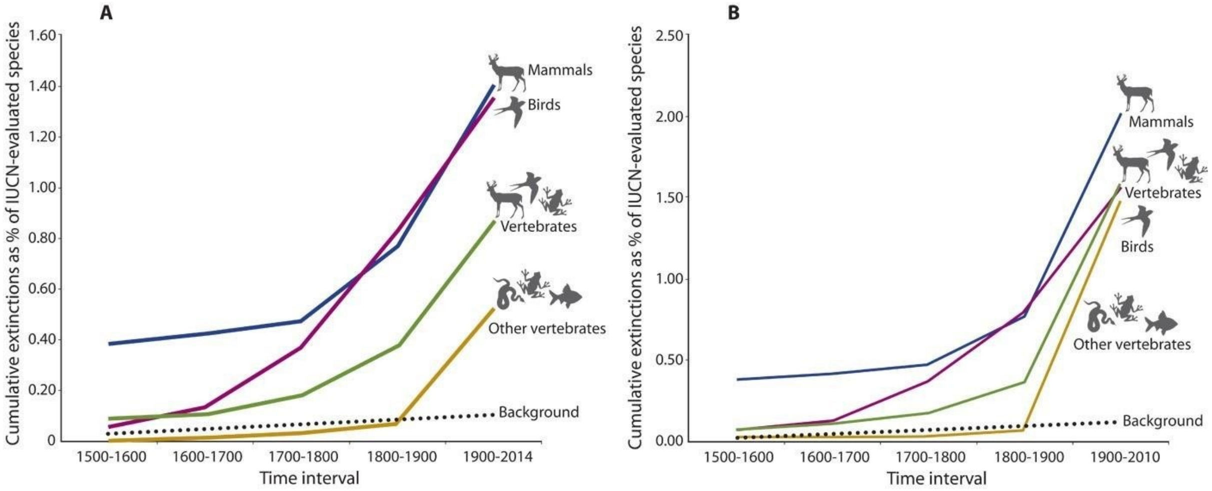

Figure 1: Proportions of extinguished species: (A) Highly conservative estimate. (B) Conservative estimate. (source: https://doi.org/10.1126/sciadv.1400253)

Here we are mainly concerned with metrics for species protection, but we also ask how these relate to metrics of ecosystem intactness such as MSA[4]. Species protection is anything but a theoretical issue. In many taxonomic groups, over 1% of species are already lost forever, with accelerating extinction rates (Figure 1).

Numbers of extinct species are known only with some lag because most extinctions occur slowly, can involve large random fluctuations of population sizes in the final phase, and the last representatives of a species may be living in some remote area and so be difficult to observe. Some species even go extinct before they are scientifically described. What we can measure much better are changes in the

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[3] European Commission, Directorate-General for Environment, 2019. Attitudes of Europeans towards Biodiversity (Report No. 481), Special Eurobarometer. European Commission. http://doi.org/10.2779/456395

[4] Mace, G.M., 2005. An index of intactness. Nature 434, 32‑33. https://doi.org/10.1038/434032a;
Faith, D.P., Ferrier, S., Williams, K.J., 2008. Global Change Biology 14, 207–217. https://doi.org/10.1111/j.1365-2486.2007.01500.x

extinction risk of known species. IUCN's Red List Index[5] and the Living Planet Index (LPI) published by WWF are leading indices for this risk at the global level, informing policy and the public at large of global trends. In the remainder of this section, we first briefly explain the MSA State Indicator Metric and then contrast this with the LPI. We also briefly discuss the relation between LPI and the Red List Index.

2.1 MSA as State Indicator Metric

The Mean Species Abundance (MSA) has been designed as the measure of local ecosystem intactness[6]. The MSA of a spatial grid cell is computed as the arithmetic mean of the abundances of all species populations, each normalised to a local baseline. Globally averaging this value over spatial grid cells then yields the value of MSA as a State Indicator Metric. The metric can be computed based on past and current observations, but it is also possible to assess how various drivers will affect MSA in the future. An example of a tool achieving this is GLOBIO, developed by PBL in the Netherlands (Fig. 2).

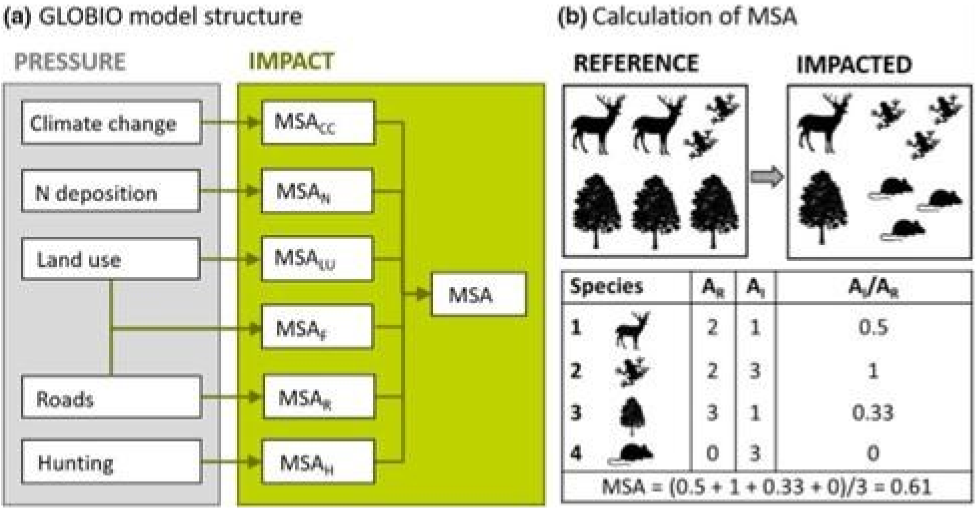

Figure 2: Structure of the GLOBIO methodology; the left-hand side shows 6 drivers that are used to calculate the MSA depending on possible future scenarios. The right-hand side illustrates how the arithmetic mean is calculated (N.B.: species, such as mice, that were not present in the reference state are not counted, and the increase in the frog population is ignored because of a truncation rule for MSA) (source www.globio.org)

2.2 The Living Planet Index

The LPI metric is by far the most widely reported metric to communicate the decline of species occurring worldwide. To understand the LPI, we need to distinguish what it aims to measure from how this is done in face of limited available data.

Conceptually, the Living Planet Index is the geometric mean of the global abundances (typically measured as population sizes) of all species in a defined taxonomic or functional group of species (e.g., all vertebrates), normalized to a baseline year taken to be 1970. The fact that this is a geometric

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[5] https://www.iucnredlist.org/assessment/red-list-index

[6] As discussed in: Schippers, A.Hilbers, J., Meijer, J., Antão, L., Benítez-López, A., de Jonge, M., Leemans, L., Scheper, E., Alkemade, R., Doelman, J., Mylius, S., Stehfest, E., van Vuuren, D., van Zeist, W., Huijbregts, M., Projecting terrestrial biodiversity intactness with GLOBIO 4 Global Change Biology, December 1st 2018, DOI: 10.1111/gcb.14848

mean rather than arithmetic mean (the normal average) is often not well explained, which can lead to confusion. Note: The geometric mean of n numbers $x_1, \ldots, x_n$ is defined as

$$\sqrt[n]{x_1 * x_2 * \ldots * x_n}$$

with x representing population size, whereas the arithmetic mean would be computed as:

$$(x_1 + x_2 + \cdots + x_n)/_n$$

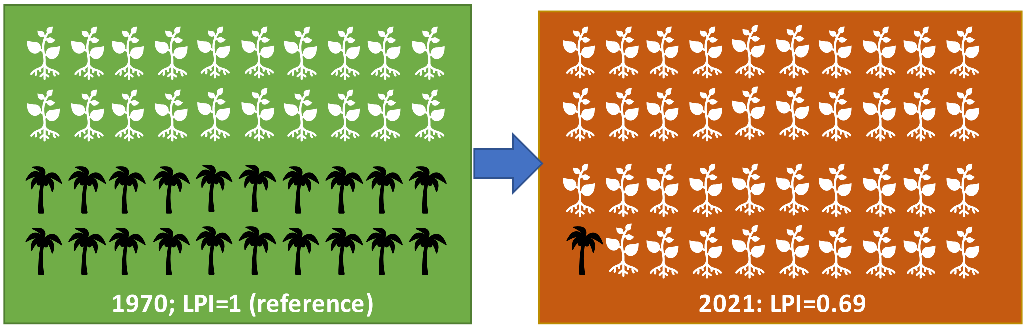

Figure 3: Example with just two species to illustrate how the LPI works; each icon represents 10,000 individuals. The decline of the palm tree (Species A) dominates the calculation, resulting in an LPI of 0.69, even though the total population stays the same

To illustrate this, consider a toy example where the group of species covered by the metric contains only two species, A and B, see Figure 2. Let's assume that in the baseline year we have globally 200,000 individuals of Species A and 200,000 individuals of Species B. The geometric mean of two identical numbers is the same as the number, here 200,000, and the LPI for the baseline year is by definition equal to 1. Now let's assume that by today the population of A has declined to 10,000 and has been replaced by species B, so that the population of B is now 390,000 individuals. This gives a geometric mean of sqrt(10,000 * 390,000) ≈ 62,450[7]. Normalizing by the baseline year, we get an LPI of 62,450/200,000 ≈ 0.31, that is, it declined by 69%. This is identical to the decline of the LPI by 69% published by the WWF in 2022. On the other hand, neither sum nor arithmetic mean of the two populations have changed since the baseline year.

A further decline of population A and corresponding increase in B can generate further dramatic decline in LPI. In general, LPI is highly sensitive to the sharp decline of a small proportion of the species it represents (Fig. 3)[8]. At first sight, this might be seen to be an artefact of the LPI. However, the mathematical analysis shows that for the purpose of quantifying extinction risk this is a desired property, as indeed sharply declining populations do indicate a sharp rise in extinction probability, and this is what LPI should signal. On the other hand, the near doubling of the population of Species B assumed in our example has hardly a significant influence on extinction risk[9].

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[7] We will use Excel notation for formulas throughout, so readers can reproduce and modify examples by pasting them as formulas into Excel sheets.

[8] Leung, B., Hargreaves, A.L., Greenberg, D.A., McGill, B., Dornelas, M., Freeman, R., 2020. Clustered versus catastrophic global vertebrate declines. Nature 588, 267–271. https://doi.org/10.1038/s41586-020-2920-6

[9] https://arxiv.org/abs/2111.03867

Since LPI responds to changes in the average extinction risk, a moderate decline of LPI can signal a moderate overall increase in the extinction risk for all the species it covers or a sharp increase in the extinction risk of a fraction of these species. As illustrated in Fig. 4, such uneven changes in extinction risk have indeed occurred in the past.

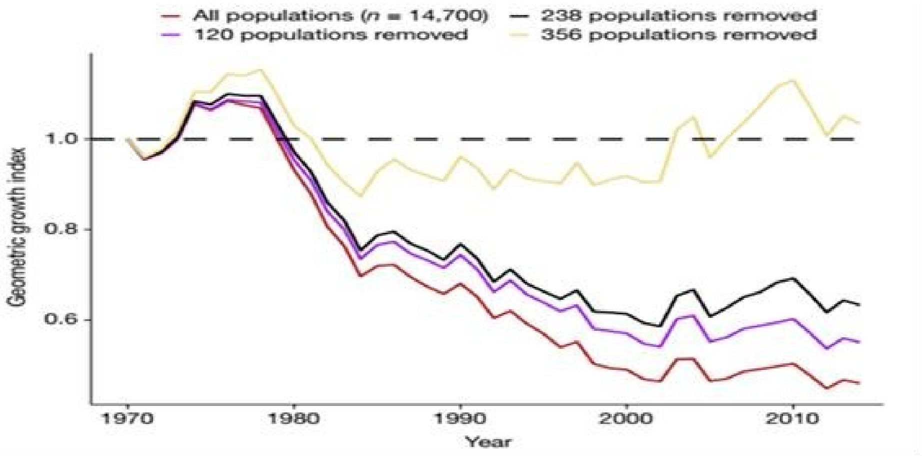

Figure 4: Leung et al. analysed the timeseries used in the LPI reports and analysed which of the 14700 populations had the most dominating effect on the outcome. Removing 2.4% or 356 fast declining populations, they turned the decline reported by the WWF in a more or less stable situation. Of course, this removal is distorting the outcome, but it illustrates the sensitivity to a fast decline of a limited number of species

In practice, the LPI is not simply computed from the geometric mean abundance of all the species it covers, because for most species the required population data is not available. Instead, the published metrics is computed from a large database of empirical population time series maintained by the Zoological Society of London. These time series often represent only local sub-populations, do not span the entire time from 1970 to the present and are uneven in their coverage of regions and taxonomic groups. The methodology for computing the published LPI has gradually been improved to overcome these distortions. The ultimate objective, however, has not changed, which is to estimate the geometric mean abundance of species in comparison to 1970.

2.3 LPI and MSA quantify different aspects of biodiversity

While the LPI is based on the geometric mean abundance of species, the mean entering the MSA (“Mean Species Abundance”) is the conventional arithmetic mean. This has profound consequences for the information provided by the two metrics.

Above we have already discussed a situation where the values of the geometric mean (which forms the basis of the LPI) changes while that of arithmetic mean (which forms the basis of MSA) does not. In many applications of the MSA (for instance in GLOBIO) a truncation rule is applied, which means increases in species are ignored (see figure 2 in section 2.1, where the increase in the frog population is ignored). If this rule would be applied in the pet example illustrated in figure 3, the MSA would change. Species population A would be truncated to 200,000, while species population B would decline to 10.000. The MSA would have become equal to (1+0.05)/2 = 0.525. However, when there is no truncation rule, or when the species population A would already have declined, some MSA calculation procedures would result in an MSA=1.

To understand better what kind of information the two metrics provide, consider a toy example with a "world" consisting of six patches of equal size that is inhabited by three species: A, B, and C. This simple world is depicted in figure 5 below. Under natural circumstances, assumed to represent our baseline, Species A lives only in patches 1-3 and B only in patches 4-6. Species C is cosmopolitan, living in all patches 1-6. Assume that all populations have the same size where they are present. We now compare the impacts on LPI and MSA of removing either Species A or Species C from patches 1 and 2. For MSA, the effect is the same in both cases: after species removal, we have MSA = 0.5 in patches 1 and 2 and MSA = 1 in patches 4-6, giving the global average MSA over patches (spatial grid cells) of (0.5 + 0.5 + 1 + 1 + 1 + 1)/6 = 0.83.

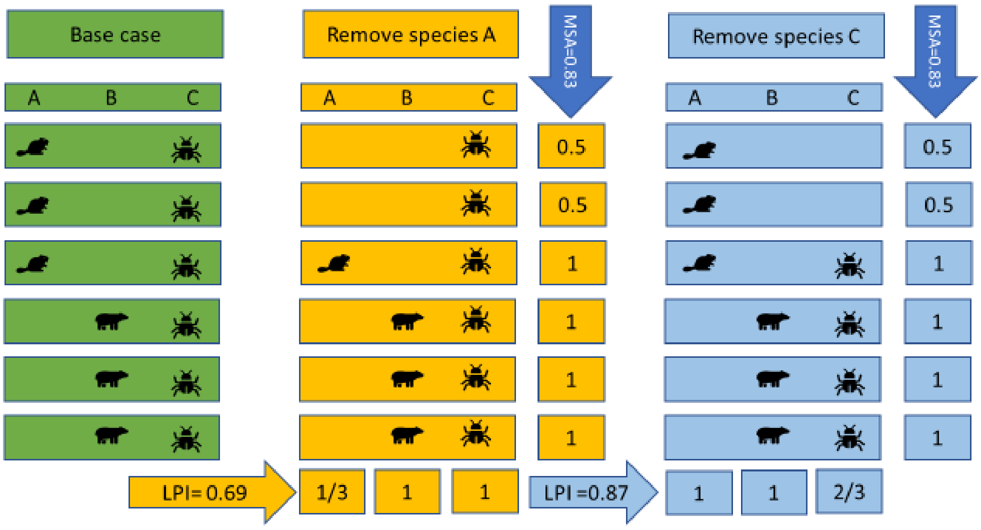

Figure 5: Assume 6 plots (or spatial grid cells) with one specie C on all plots, one species A on the first three and another species B on the last three. This example shows that the LPI is sensitive to the number of plots where the species occur while the MSA metric is not, see text above

In terms of LPI the impacts differ. If Species A is removed, this reduces its population to 1/3 of its baseline value. LPI can be computed as the geometric mean of the population sizes relative to baseline, which gives (1/3 * 1 * 1)^(1/3) = 0.69. When removing instead Species C from patches 1 and 2, its population decays to 2/3 of its original size, giving an LPI of (1 * 1 * 2/3)^(1/3) = 0.87.

These numerical differences reflect the different components of biodiversity that the two metrics are designed to represent. Absent of further information, we need to assume that loss of Species A from patches 1 and 2 affects ecosystem intactness there just as much as loss of Species C. Hence the value of MSA does not change. It does not depend on the identity of the removed species. In terms of extinction risk, the effect of removing Species A from patches 1 and 2 is more severe than that of removing Species C. Removing Species A would leave it occupying just a single patch and loss of this final patch would entail its irrevocable global extinction. The effect of removing the cosmopolitan Species C from patches 1 and 2 is less severe. Correspondingly, LPI, as a measure of impact on extinction risk, declines by 31% in case of Species A removal but only by 13% when removing Species C.

2.4 The IUCN Red List Index

The IUCN Red List Index is another State Indicator Metric for extinction risk. Conceptually, it is obtained by assigning the values 0, 0.2, …, 1 to the Red List classifications of species as Extinct, Critically Endangered, Endangered, Vulnerable, and Near Threatened and Least Concern, respectively, and averaging over all species in a taxonomic group. Red List classifications are, in turn, based on various combinations of criteria such as species population size, trends in populations size, causal explanation of trends, and estimated probability of extinction.

Compared to the LPI, which is based on population sizes only, the Red List Index therefore has the advantage of taking more information into account to gauge global extinction risks. The price to pay, however, is that the quantitative interpretation of the metric is less obvious and that computing it is more laborious than for the LPI, leading to less frequent updates.

3 Footprint Metrics

Metrics assessing biodiversity on the global scale are needed, but, as such, may not help improving the state of biodiversity. Changes in the state of biodiversity can only come if various stakeholders such as companies and financials change the way they operate. These stakeholders generally use a different type of metric, often referred to as footprints, to understand and quantify the impacts their activities cause, and use this as input to their "Plan, Do, Act, Check" management cycles. For this, an organization might, for example, determine its carbon footprint, water footprint, and, since a few years, biodiversity footprint.

Biodiversity footprinting tools are designed to understand and report the level of impact an organization has on the decline or restoration of biodiversity and the main causes leading to this impact. With this insight they can prioritize mitigating actions.

Figure 6: Footprinting methods do not consider the impacts from the past, but what the impacts of a current economic activity is in the future; in this example one species may have disappeared from a certain region due to an intervention. For instance, the release of CO_2 will contribute to a long-term change in temperature, which can cause certain species to disappear from a region in the next 100 years or so[10]

We will now describe a widely used Footprint Metric based on the concept of PDF, which stands for Potentially Disappeared Fraction of Species. The main focus in this chapter will be on the PDF metric. As we will explain in Chapter 4, this has, amongst Footprint Metrics, the best link to LPI. However, we will also touch upon the use of MSA as a Footprint Metric.

3.1 Potentially Disappeared Fraction (PDF) metric

The notion of the Potentially Disappeared Fraction (PDF) of species was introduced in the context of life-cycle assessments (LCA) around 1999 as a measure of the local "damage to ecosystems" caused by specific anthropogenic pressures.[11] Conceptually, it is the probability that a species that is randomly chosen amongst all species present at a spot will get extirpated (i.e., locally disappear) at this spot as a result of this pressure. A PDF of one means that all species are locally lost, a PDF of zero that no species are lost under a given pressure. Use of PDF for biodiversity footprinting requires that we compute the combined local impacts from several kinds of pressure in terms of PDF and then sum these impacts over Earth's surface. A detailed, publicly available methodology for doing this is ReCiPe[12].

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[10] This means we integrate the future impacts from an emission over time. This is best illustrated using the case climate impacts. The IPCC published CO_2 equivalents depending on how long the future is integrated: 20, 100 of 500 years. Methane has an environmental lifetime of 2-3 decades, while CO_2 has a lifetime of 150 years. So, if we take the 20 years timeframe almost all impacts from a methane emission are captured, but only approximately one eights of the CO_2 impacts, while in a 100 year timeframe the impacts from both substances are captured. In ReCiPe a cut-off time of 100 years is used for climate and for all other substances with long life time.

[11] Goedkoop *et al.*, The Eco-indicator 99, https://pre-sustainability.com/articles/eco-indicator-99-manuals/

[12] https://www.rivm.nl/en/life-cycle-assessment-lca/recipe. ReCiPe is also used for biodiversity footprinting by financials, frequently connected to the Partnership for Biodiversity Accounting Financials or PBAF (https://www.pbafglobal.com)

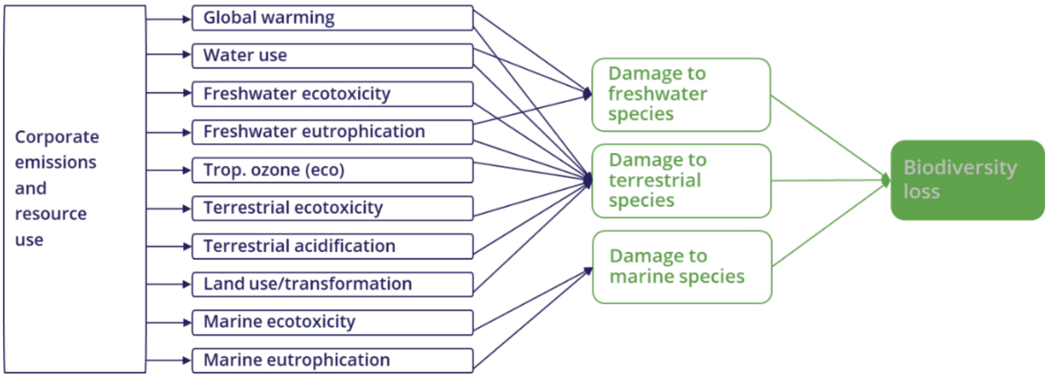

Figure 7: Structure of the ReCiPe model that is used to calculate the PDF based metric (source: Author) Figure 7 shows the ten cause-effect mechanisms that are taken into account in ReCiPe. While we cannot explain these in detail here, it is important to understand the principle of how the release of a specific emission (measured in kg) enters ReCiPe

The footprinting methodology used in ReCiPe considers that any emission will spread out over space and eventually, if gradually, decline. The impact is therefore not quantified simply as PDF, but as PDF multiplied with the effective size of the area affected and the effective duration of this effect. The methodology accounts for the fact that the effects are distributed unevenly in both space and time by modelling their distributions using 'fate models' specific to the kind of emission considered. This implies that the effect size is given in dimensions of PDF × Area × Time and measured in units of PDF.m2.yr. For aquatic ecosystems, where a water volume is affected, the corresponding measure is in PDF.m3.yr.

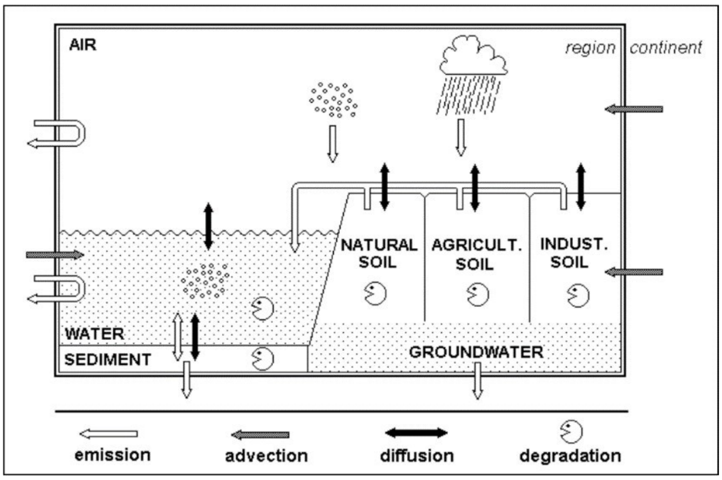

Figure 8: A simple representation how the 'fate' of an emission can be modelled. If, for instance, a toxic emission is released to the air, it can have direct impacts through breathing, depending of the concentration. The concentration will gradually decline as substances do break down and partially transfer to water and soil. If they enter agricultural soil, a fraction will enter the food chain. The model can handle a large range of substances if a number of substance properties are known. Fate modelling is continuously improving, and similar models are available for non-toxic substances. Source: EUSES[13]

For land occupation, a different approach can be used. If a farmer occupies a certain area the input parameter already has units of m2.yr; the way the land is managed determines the PDF, resulting in an effect with units PDF.m2.yr.[14]

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[13] Jager, D.T. et al.: EUSES the European Union System for the Evaluation of Substances. National Institute of Public Health and the Environment (RIVM), The Netherlands; Available from the European Chemicals Bureau (EC/JRC), Ispra, Italy 1996.

[14] For land transformation it is assumed that the actor transforming the land is responsible for its restauration and the impact during the restauration period (which can be significant) is attributed to the actor that converted the land in the first place.

If the assessment yields a result of 100 PDF.m2.yr it means that all species have disappeared from 100 m2 during a year, or 10% of the species have disappeared from 1000 m2 during a year, or 10% have disappeared in 100 m2 during 10 years.

For a company that assesses the impacts of its annual emissions, the value of year becomes 1. If it assumes that all species disappear (PDF=1), the company can communicate a number of equivalent m2 in which all species are lost. In Chapter 4 we shall also discuss another way of reporting ReCiPe results, by linking the metric to species density.

It is important to keep in mind that this metric does not quantify the instantaneous impact of business activity over a year. Some impacts of business activity are felt many years later. This is comparable to CO_2 equivalents which are reported as an annual impact, while in fact the consequences of the CO_2 emissions will occur in the future. The annual impact quantifies the long-term biodiversity impact that the business would have if it indefinitely continued with the same activity at the same rate of emissions.

3.2 MSA as a Footprint Metric

Above we described MSA as it was originally conceived, to compute global Mean Species Abundance (MSA) as a state indicator. But it can also be used as a footprinting tool[15]. This is possible as one of the most widely used tools to calculate MSA, called GLOBIO, has quite a similar structure as the ReCiPe tool that is used to calculate the PDF metric. In fact, GLOBIO and ReCiPe both come from the Netherlands and there is an overlap in authors of the publications. The use of GLOBIO for footprinting generates impacts measured in units of MSA.m2.yr by the same reasoning as used in ReCiPe.

In addition, the drivers considered in ReCiPe and GLOBIO are based on almost the same models and underlying science, e.g., with regards to climate, land-use and nitrogen. ReCiPe does not specifically model roads, disturbance and hunting, while GLOBIO misses drivers such as water scarcity, land conversion, acidification, toxicity etc see Figure 7.

Resulting from their similarity, GLOBIO and ReCiPe do indeed generate similar (but inverse) outputs (Fig. 9).

Figure 9: Taking up the example of Figure 5, illustration of the inverse effects of local species loss on MSA and PDF in simple cases. In these cases, the footprinting MSA is equivalent to 1-PDF.

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[15] We refer to the Global Biodiversity Footprint developed by CDC in France: https://www.cdc-biodiversite.fr/publications/global-biodiversity-score-establishing-an-ecosystem-of-stakeholders-to-measure-the-biodiversity-performance-of-human-activities-2/ as well as the Product Biodiversity Footprint by I-care and Iceberg Datalab: http://www.productbiodiversityfootprint.com/

4 Bridging the Gap

Having discussed state indicators (LPI, MSA) and the Footprint Metrics based on PDF and MSA, the question arises if and how these can be linked. As shown above, the two state indicators measure different things, providing different information to policymakers.

The link between the state indicator MSA and the footprint indicator MSA is relatively simple, but as we saw in Chapter 2, the MSA state indicator is not as sensitive to extinction risk as the LPI is. The MSA indicator can be seen as an indicator addressing ecosystem intactness and the resulting potential to provide ecosystem services. For a policy objective focused on lowering extinction risk, policy makers are likely to use the LPI metric. From our analysis the best linkages can be made between the LPI State Indicator Metric and the PDF-based Footprint Metric. We will also briefly discuss other metrics that can be linked to LPI and PDF to assess compensatory measures.

4.1 Linking PDF-based metrics to the LPI

PDF-based metrics can be understood as approximately measuring the impact business activity has on the LPI. The detailed analysis finds that ΔLPI ≈ - PDF*LPI, with LPI denoting the value before the change and ΔLPI the size of the change.

To see this, consider first an idealized situation with 5 different drivers acting such that the resulting PDF is the same in all 5 plots; in Figure 10 below, we assume each plot loses one out of 10 species (but a different species per plot). All 5 plots have an identical species composition from the onset. Some species are represented by 200 individuals, others by 2000, resulting in population sizes of 10,000 or 1000 individuals over the 5 plots. We then remove some species at some plots and find that above equation holds to a good approximation.

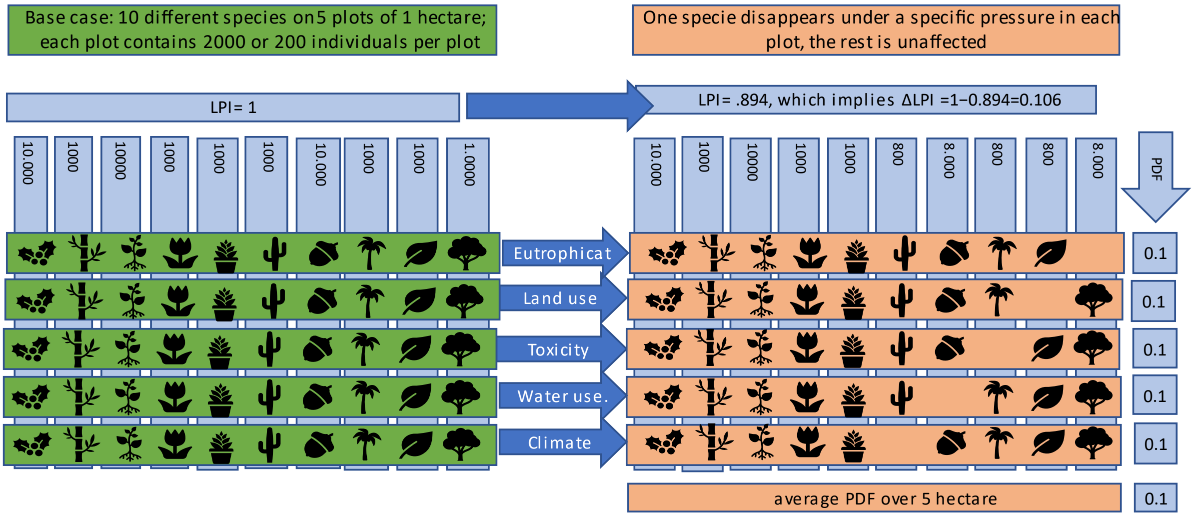

Figure 10: Example in which 5 plots contain the same species composition and the same number of plants per plot (either 200 or 2000, resulting in a total of 1000 or 10,000). The pressures cause disappearance of one species in each plot; we assume they are different species

In this example we consider 5 different plots that are each affected by a different pressure, which causes one species to disappear from that plot. We assume they are each different species. The pressures cause a PDF of 0.1 (10% of the species are gone) in each plot. As this happens over all 5 plots, the average PDF is also 0.1.[16] To calculate the LPI we first consider the losses of each species, summing the abundances along columns. Five species do not change; the other 5 species see a population decline of 20%. The latter implies that the LPI becomes 0.894 and so ΔLPI is -0.106. This value is quite close to the average PDF value.

One numeric example does of course not prove much. It could be coincidental or engineered to prove the point. In the original paper mentioned in the title page a general mathematical argument is provided that shows that we can generalize this finding under the condition that the footprint results do not report big changes and that the impacts are widely distributed over a large area. This is often the case when supply chains are assessed. It is quite easy to see that the example would not prove our point if the footprint would cause all acorns to disappear from all 5 plots while not affecting the other species. In that case the LPI value would become zero, while PDF would still be 0.1.

4.2 Some more details on the assumptions and validity of the PDF-LPI link

The formula ΔLPI ≈ - PDF*LPI does not necessarily require that local impacts in terms of PDF are the same everywhere as we assumed in the example. Often one can simply use the global average of PDF in the formula, especially when there is no strong correlation between PDF and local species density[17].

Correlations can be dealt with by multiplying local PDF-values by local species density[18]. In fact the ReCiPe methodology does propose this as a way to reconcile surface-based metrics and volume-based metrics, respectively, PDF.m2.yr and PDF.m3.yr. When these results are multiplied with the species density[19] in terrestrial, freshwater and marine water systems, measured in units of species/m2 or species/m3, this converts biodiversity impact measures in terrestrial, aquatic and marine ecosystems into a metric measured in species.yr:

- PDF.m2.yr × species/m2 = species.yr
- PDF.m3.yr × species/m3 = species.yr

This metric is not only useful to reconcile the volume and surface-based impacts, but it also expresses the potential disappearance of a fraction of species (during a year) from the planet. This does not necessarily mean the species go extinct, as PDF in principle expresses a temporary disappearance. The original mathematical analysis on which this paper is based discusses these issues in more detail (see introduction).

By the close relation between LPI and average extinction risk noted above, this use of PDF-based metrics provides a measure for the impact of business activity on the average extinction risk of species.

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[16] If there were not 5 plots, but all pressures were exerted on the same plot, half of the species would be gone, which would mean a PDF = 0.5. The approximation is only valid if the loss of species happens over a wide area and different species have different sensitivity to the same or different pressures.

[17] https://arxiv.org/abs/2111.03867

[18] On spatial scales smaller than typical species range sizes, the metric called Range Size Rarity should be used for weighing, which reduces to species density on larger scales.

[19] In ReCiPe the following species numbers are used: terrestrial species: 1,600,000; freshwater species: 100,000; marine water species: 250,000.

5 Compensating impacts

5.1 Biodiversity Stewardship Credits

This paper does not advocate the idea that all impacts should be compensated, as the first priority is to reduce impacts. However, there will always be residual impacts from almost any operation and it is important to understand metrics that can be used to gauge the extent of compensatory measures.

Above we have seen how the PDF Footprint Metric can be understood as an approximate measure of impact on LPI that works particularly well when impacts are widely dispersed. In other situations, such as more localized impacts or impacts affecting only a small number of species, other metrics can be used to estimate how they affect LPI. These different kinds of metrics all provide approximate numerical answers to the same question: how much does/did LPI change as a result of some action? We want to show that such metrics are comparable with and convertible into each other, provided they are used in circumstances where the underlying approximations are valid.

An example of a metric that can assess compensatory measures on a more local scale is the Biodiversity Stewardship Credits (BSCs) concept. The BSC metric is defined, for a given area of land or water, in the following way. First a relevant species group is defined. Then the local population size of each species in the group is compared with (divided by) their global populations. Then these shares (fractions) are added.

When the BSC metric and the LPI are computed for the same group of species, and writing S for the total number of species entering the LPI, then BSC divided by S approximately predicts the proportional amount why which LPI would change when all species would be fully eradicated from the area of land considered. More generally, the local change in BSCs over time (ΔBSC) can be used to approximate the resulting change in LPI:

$$\Delta \mathrm{LPI} \approx \Delta \mathrm{BSC} * \mathrm{LPI} / S.$$

This approximation works particularly well when all local populations contribute only a small proportion to their global populations. Otherwise, a slightly modified metric should be used.[20]

From the definition of BSCs it follows that widely distributed species with large global populations tend to make rather small contribution to BSCs, while those species that exist only in or near the affected area can make a particularly large contribution. The BSC metric thus intrinsically draws attention to species that are threatened with extinction, as expected from its close mathematical relation to LPI.

We can again illustrate this with an example (Fig. 11), which is very similar to the example in Fig. 10. We now focus on plot 5, where 50% of the acorn species were gone due to prior activities. When an actor restores this reduction and ensures all acorns will thrive again, we can calculate the BSC, the PDF and the LPI.

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[20] https://doi.org/10.48550/arXiv.2111.03867

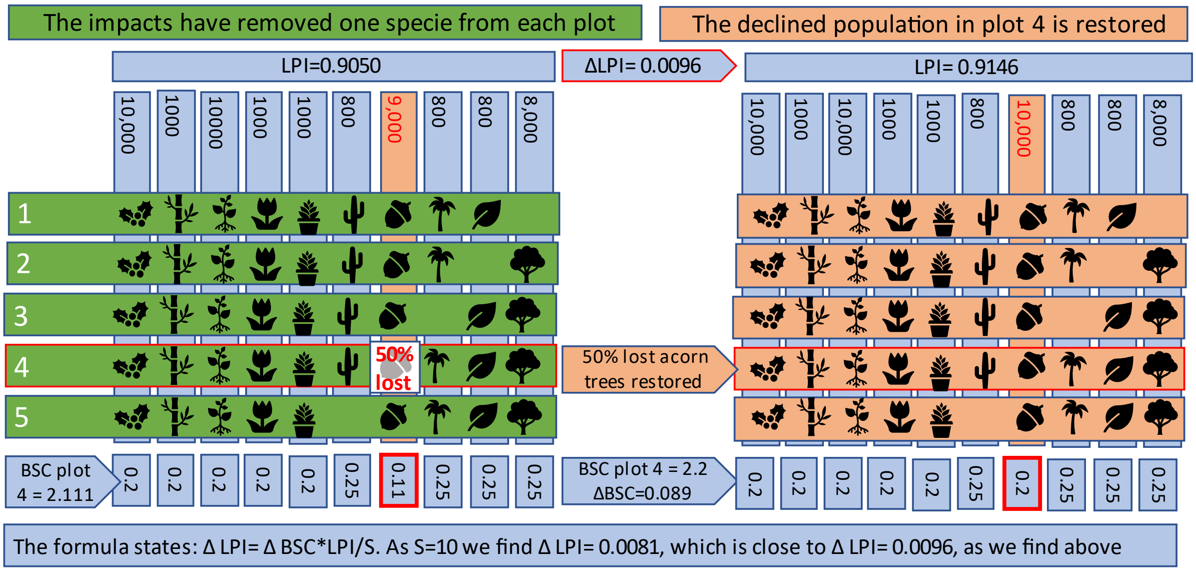

Figure 11. Example in which 50% of the acorn species loss on plot 4 is restored by compensating measures, while the other plots are unchanged (cf. Fig. 10). The restoration of the acorn population (from 50% to 100%) leads to an improvement of the LPI of 0.0096. We now test the prediction ΔLPI ≈ ΔBSC * LPI / S. The formula for calculating the BSC in our example is $BSC=\sum n_{plot4}/n_{all\_plots}$, meaning that we divide for each species the population in plot 4 by the population in all plots and then sum over all species. In the reference situation the BSC metric of plot 4 is then 2.111; in the situation where the diversity in plot 4 is restored it increases to 2.2; which means the change ΔBSC is 0.089. This leads to the prediction ΔLPI ≈ ΔBSC * LPI / S = 0.0081 (with S=10, the number of species). The predicted value is not exact, but rather close to the calculated ΔLPI = 0.0096

For businesses, financial institutions or other organisations aiming to reduce their impacts on mean long-term species extinction risk, or even aiming to make a positive biodiversity impact by reducing this risk through their operation, BSC and related metrics can be used to quantitatively demonstrate the effectiveness of their efforts. Organisations might generate positive ΔBSC by supporting the growth of rare species in the land they hold or might partner with specialist providers for this goal. The numerical comparability of ΔBSC/S with global mean PDF can be used to set the positive impacts an organisation produced (as measured by ΔBSC/S) in relation to its negative impacts (as measured by global mean PDF). If the positive impacts are much larger than the negative ones, one can be safe to assume that the overall impacts of this organisation's operation on LPI and on global long-term species survival are positive and the organisation is biodiversity positive in this sense.

A good example of the application of this thinking can be found in the work of the Tree Conservation Fund[21], where companies are invited to invest in restoring the population of one or several endangered tree species.

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[21] https://www.treeconservationfund.org/

5.2 Other related metric: STAR and Range Size Rarity

Depending on data availability and the nature of the impact in question, other approximate Footprint Metrics can be constructed to quantify impacts on LPI. For example, available data is often sufficient to compute the range of a species but not its global abundance. In this case, one can approximate proportional change in species abundances by proportional changes in their ranges. This leads to the Range Size Rarity (RSR) metric, which is computed by first calculating, for each species on the land held by an organization, the proportion that this land contributes to the species range and then adding these contributions. An RSR value so computed can be used to estimate the corresponding BSC value and interpreted in the same way.

The START metric, which has been designed as a Footprint Metric related to the IUCN Red List Index, is a variant of RSR, with species weighted by their IUCN Red List conservation status and, in some forms of the metric, by causes of extinction risk. The additional information entering IUCN Red List status can be useful to anticipate future population trends if such information is required. RSR, on the other hand, is conceptually simpler and can, similar to BSC, mathematically be linked to LPI. Objectives and thinking underlying the construction of RSR and START, however, are very similar. At global scale, variations in species range sizes due to geographic constraints dominate variability in both RSR and START, which is why the two metrics are correlated and can be converted into each other on this basis.

6 Conclusions

The mathematical analysis presented in the accompanying report by co-author Axel Rossberg shows how Footprint Metrics such as PDF, state indicator metrics such as LPI, and others are linked. A particularly interesting finding is that state indicator metrics such as LPI and Footprint Metrics such as PDF have a clear relationship. This is remarkable, as they are seemingly based on very different calculation procedures. LPI is based on changes in species abundances, while the PDF metric does not consider this, but only reports the disappearance of species.

This opens up an important possibility for users of footprint indicators, such as companies and financials, to report their impacts and their progress towards reducing their impacts in a currency relevant to users of state indicators, such as governments and NGOs. We have demonstrated in particular that the relatively simple PDF metric, used in the right way, can approximate contributions to changes in the LPI metric, quantifying changes in species extinction risk. With regards to local ecosystem intactness, similar relations between state- and footprinting metrics can be established in the case of MSA.

Crucial to our approach is the realisation that various metrics and their utility derive from their ability to approximate in simplified forms a quantity of wide public interest: changes in the mean long-term extinction risk in the group of species considered. The LPI metric achieves this in the form of a state indicator. The PDF metric does so by approximating impacts reflected in the LPI metric. The approximate relations that we demonstrated are valid only when changes in population sizes are limited. As we explained, the LPI metric is sensitive to fast declines in the population sizes of a small proportion of species, while PDF (as MSA) is not sensitive to this. This limitation is acceptable, as businesses who calculate and report footprints will not generally cause a very rapid decline in the global population of a species, at least not on their own. Large trends in population sizes are generally caused by the combined action of many businesses and other actors, unless a business operates in an area where it impacts the last remaining individuals of some species at high extinction risk. In such cases the approximation of changes in LPI by the PDF metric do not work. However, alternative impact metrics are available in such cases, including BSC, Range Size Rarity, or STAR, from which good estimates of the resulting change in LPI can be obtained. When understood as approximations valid only in prescribed circumstances, it becomes clear how these metrics can quantify the same thing in convertible currencies despite being computed in different ways.

In this paper we tried to illustrate the key findings in extremely simplistic examples. The next step would be to apply these findings in more sophisticated, real-life examples and to develop some case studies. We would also like to invite comments from experts, as we see this as the start of a development which aims at bringing different schools of thought, each using (and liking) their own metric, together and so to improve our means to assess the state of biodiversity.