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Abstract

Business and finance sector actors have the potential to contribute substantially to bending the curve of biodiversity loss, in the context of a global nature positive agenda. The scope of application of the mitigation hierarchy – avoiding and reducing negative impacts on nature, and compensating for the residual ones – is being extended, from localised impacts to potentially diffuse ones at the level of corporate value chains, to achieve at least no net loss (NNL) of biodiversity. This poses a need to define and quantify the equivalence of biodiversity losses and gains, which may depend on the metric(s) used to measure them. Here we evaluate and compare three biodiversity metrics in a global NNL context, using an optimization approach to identify the minimum area to be restored in order to compensate for biodiversity losses from corporate activities. The three metrics are Mean Species Abundance (MSA), the Land-cover Change Impacts on Future Extinctions (LIFE) score and the Species Threat Abatement and Restoration (STAR) metric. We also investigate how spatial scale constraints imposed on restoration affect the achievement of NNL across metrics. We observe cases for all metrics where NNL cannot be achieved within strict spatial scale constraints. We also find that NNL for one metric does not guarantee NNL for the others, and that differences in the nature of the metrics (MSA, compared to LIFE/STAR) influences the overall area restored to achieve NNL. The results highlight how outcomes for biodiversity will be more satisfactory if using two or more complementary metrics for value-chain level NNL assessments, and how avoiding and minimizing losses is key, as compensation within certain spatial constraints is not always possible.

1. Introduction

In the face of the current biodiversity crisis, bending the curve of biodiversity loss is increasingly urgent (IPBES, 2019). Business and finance sector actors, among others, have the potential to contribute substantially to this goal (Mace et al., 2018). Target 15 of the Kunming-Montreal Global Biodiversity Framework (GBF) specifically aims to reduce the negative and increase the positive impacts of business on biodiversity and to encourage more sustainable production (Convention on Biological Diversity, 2022). Stemming corporate losses of biodiversity is linked to the concept of "no net loss" (NNL) (Robertson, 2000), frequently referred to in development projects (Maron et al., 2018). According to the mitigation hierarchy, adverse impacts on biodiversity should first be avoided as much as possible, then minimised; restoration should then be implemented for the biodiversity that has been impacted, and remaining residual impacts should be offset in order to achieve (at least) NNL (BBOP, 2012).

In practice, current offsetting – whether regulatory, required by funders or voluntary (Bull and Strange, 2018) – focuses on impacts of direct operations on a defined set of priority biodiversity features. Approaches to dimensioning the offsets differ, but often include both overall ecosystem area and condition (Gardner et al., 2013), as well as priority features (species and/or threatened/distinctive ecosystems) considering irreplaceability and vulnerability (Gonçalves et al., 2015). For example, the International Finance Corporation's (IFC's) Performance Standard 6 includes provisions for both natural habitats and critical habitats, *e.g.* that include highly threatened species or constitute unique ecosystems (IFC, 2012). The DEFRA Biodiversity Metric, for measuring compulsory biodiversity net gain of developments in the UK, accounts for habitat area, quality, distinctiveness and its local strategic significance (DEFRA, 2024). Offsets involve equivalence requirements, with limited fungibility between losses and gains of different biodiversity features (Gardner et al., 2013). Measuring outcomes directly at the sites of impact instead of through indirect techniques is recommended (Gardner et al., 2013). Dimensioning of offsets depends on the metrics used for measuring losses and gains: in an Uzbek region, offset requirements for oil and gas infrastructure varied by up to an order of magnitude, and did not always lead to NNL, across a range of species- or habitat-based methods used for calculating the required gain (Bull et al., 2014). Similarly, Marshall et al. (2022) found different offset requirements and outcomes for simulated developments in Australia depending on the habitat- or species-based biodiversity metric employed.

However, attention of business and finance is now moving beyond direct operations to the value chain; reducing and compensating impacts up- and downstream, with commitments to achieve NNL and even a net positive impact (NPI) at the corporate level (Rainey et al., 2015; Silva et al., 2019; zu Ermgassen et al., 2022), in the context of nature positive approaches (Business for Nature, 2022; ICMM, 2024; Locke et al., 2021; Milner-Gulland, 2022). Here, loss-gain accounting is much less clear-cut with regard to assessing both impacts and gains expected from the compensation actions, as well as the equivalence of the two (Maron et al., 2023), since measures of biodiversity are contingent on the scale of the analysis and the metrics chosen (McGill et al., 2015). For example, evaluating the risk of vertebrate biodiversity loss from soy production in Brazil, Argentina and Paraguay, Molotoks et al. (2023) found different hotspots of threat dependent on the group of species selected (threatened, endemic, affiliated to forest habitat, or all species). Countries identified as having higher consumption-based biodiversity footprints differ when calculated with metrics of alpha or gamma diversity (Marquardt et al., 2019). Each metric of biodiversity is a proxy for one or several component(s) of biodiversity's complexity. Corporates may choose metrics that can track prioritised components of biodiversity and also support value-chain measurements, potentially across the globe. Dimensioning and measuring achievement of NNL at the value-chain level implies some level of aggregation of dispersed and dissimilar impacts – on different ecosystems, species, *etc.*

– into a single assessment. In many cases, incomplete knowledge of the exact location of a corporate's impacts creates a further complication. The feasibility of demonstrating NNL at value-chain level likely is influenced both by the choice of loss-gain metric(s) and the scale at which they are aggregated and/or considered fungible. However, quantification of this influence for metrics that are already being used to track biodiversity impacts in corporate contexts has yet to be fully explored.

To address this, we examine the degree with which a restoration plan designed to achieve NNL when using a given biodiversity metric also achieves NNL as measured with alternative biodiversity metrics. We also examine how spatial scale constraints on restoration (related to either administrative or ecological boundaries) influence the area requirements for NNL and whether it can be achieved. To do this, we develop and apply a framework to assess required NNL actions for activities inducing biodiversity loss in different locations (*e.g.*, for value chains) in relation to the choice of the metric used to measure biodiversity losses and gains, and to the scale at which NNL is defined. For fictitious value-chain biodiversity losses we compare restoration requirements to achieve NNL for three metrics and three geographical constraints: anywhere globally (no constraint), within the countries of the losses (economically and politically relevant scale), and within the ecoregions of the losses (ecologically relevant scale).

The metrics assessed are Mean Species Abundance (MSA), the Land-cover change Impacts on Future Extinctions (LIFE) metric and the Species Threat Abatement and Restoration (STAR) metric. MSA is a measure of ecosystem condition, quantifying local biodiversity intactness at the assemblage level (Alkemade et al., 2009), while LIFE and STAR are species-level metrics of extinction risk. LIFE measures the effect of land-use change on the extinction probability of species, relative to a historic baseline using a non-linear persistence score (Durán et al., 2020; Eyres et al., 2024). STAR quantifies the potential contribution of habitat restoration and/or threat abatement to the reduction of species' extinction risk through a linear relationship (Mair et al., 2021). These are three of many available biodiversity metrics, that were chosen since MSA and STAR are both cited in the TNFD's assessment approach (TNFD, 2023), as well as in the GBF, as complementary indicators for goal A (MSA), and targets 4 and 15 (STAR). LIFE scores are expected to be made publicly available and appear promising for a range of applications, in particular as the metric enables assessment of both continued corporate impacts and gains from restoration (Eyres et al., 2024). All three are therefore candidate metrics for assessing losses and gains in the context of nature-positive approaches.

2. Methods

2.1 Overview of the approach

We consider a number of hypothetical loss simulations, each consisting of a set of localised impacts with corresponding biodiversity loss, mimicking the multiple impacts of a value-chain (see section 2.3 for details). Per simulation, we identify the minimum localised area to restore to achieve NNL using one of the three metrics as target. We then calculate the percentage of NNL achieved as measured by the other metrics, for restoration over the same localised area. This computation is done under three different spatial scale constraints (global *i.e.* unconstrained; country; ecoregion), defining the geographic scale at which NNL is defined, *i.e.*, the scale at which losses are aggregated and where restoration can occur. We repeat the exercise changing the metric used as a target in the restoration problem, leading to nine cases: three target metrics combined with three spatial scale constraints. The following sections describe the methodology in detail.

2.2 Defining equivalence of losses and gains for each metric

For each metric we define equivalence of losses and gains of biodiversity for terrestrial ecosystems. Metric data are available at a grid cell level. We consider multiple losses and gains, each occurring in distinct grid cells. Losses are assumed to arise from corporate activities leading to a total destruction of habitat and biodiversity. Gains are assumed to arise immediately and completely from habitat restoration via land-use or land cover change, restoring a set of habitats to their original state before human intervention. Details on the definitions of the metrics are provided in sections 2.2.1-2.2.3 below and in Supplementary Material 1.

2.2.1 Mean Species Abundance (MSA)

Mean Species Abundance (MSA) is an assemblage-level measure of local biodiversity intactness (0-1, dimensionless) (Alkemade et al., 2009). Under the assumption that given corporate activities result in a complete loss of the remaining biodiversity in grid cells i, the loss of MSA can be quantified as:

$$MSA_{loss} = \sum_i MSA_i \cdot A_i \cdot f_{loss,i} \qquad \textbf{\textit{Eq. 1}}$$

where MSA_{loss} is the total loss of biodiversity (>0, expressed in MSA.km²); MSA_i is the biodiversity in cell i prior to the impact (0-1, MSA); A_i is the area of cell i (km^2); and $f_{loss,i}$ is the fraction of cell i where the impact is occurring (0-1, dimensionless).

The global data layer available for MSA evaluates remaining biodiversity by decomposing the effect of several pressures. Restoration here is assumed to only lead to gains through land-use changes, since other pressures such as climate change can continue to affect biodiversity even after habitat restoration. Thus, equivalence assumes that a loss and a gain can be expressed as $MSA_{gain} = MSA_{loss}$, with:

$$MSA_{gain} = \sum_j \frac{1-MSA_{j,LU}}{\sum_x(1-MSA_{j,x})}(1-MSA_j) \cdot A'_j \cdot f_{gain,j} \qquad \textbf{\textit{Eq. 2}}$$

where MSA_{gain} is the total gain in biodiversity (>0, expressed in MSA.km²); $MSA_{j,LU}$ is the remaining biodiversity in relation to the land-use pressure in cell j; x designates all pressures affecting MSA; MSA_j is the biodiversity in cell j prior to the restoration (0-1, MSA); A'_j is the maximum restorable area in cell j (km^2); and $f_{gain,j}$ is the fraction of restorable area in cell j that is restored (0-1, dimensionless).

Losses and gains are expressed in MSA.km² to account for the area that is affected by impacts/restoration actions.

2.2.2 Land-cover change Impacts on Future Extinctions (LIFE)

The Land-cover change Impacts on Future Extinctions (LIFE) metric is based on the persistence score (P), which reflects the likelihood that a species will persist as a function of its area of habitat (AOH) (Durán et al., 2020; Eyres et al., 2024). Thus, losses ($\Delta P < 0$) or gains of persistence ($\Delta P > 0$) can be calculated based on losses or gains in AOH. Summed across all species, this provides biodiversity losses, quantified using the LIFE score (Eyres et al., 2024) in the following way:

$$\text{LIFE}_{loss} = \sum_i \sum_s \Delta P_{i,s} \cdot f_{loss,i} \qquad \textbf{\textit{Eq. 3}}$$

where $LIFE_{loss}$ is the total loss (<0, dimensionless) of species persistence probability (P); $\Delta P_{i,s}$ is the marginal change in P for species s when cell i is completely destroyed (<0, dimensionless), independently of all other cells; and $f_{loss,i}$ is the fraction of cell i where the impact is occurring (0-1, dimensionless).

Persistence is calculated as the remaining proportion of a species AOH raised to a given exponent, taken as 0.25 in the present study and in previous ones (Durán et al., 2020; Eyres et al., 2024). A discussion on the impact of choosing a different exponent is provided by Eyres et al. (2024).

Equivalence of a loss and a gain can be expressed as $\text{LIFE}_{gain} = |\text{LIFE}_{loss}|$, with:

$$LIFE_{gain} = \sum_j \sum_s \Delta P_{j,s} \cdot f_{gain,j} \quad \textbf{\textit{Eq. 4}}$$

where $LIFE_{gain}$ is the total gain (dimensionless) of species persistence probability; $\Delta P_{j,s}$ is the marginal change in P for species s when all restorable area in cell j is restored independently of all other cells (dimensionless); and $f_{gain,j}$ is the fraction of restorable area in cell j that is restored (0-1, dimensionless).

Note that in practice $\Delta P_{j,s}$ can be negative or positive, *i.e.,* restoration can lead to a marginal loss or a gain of persistence, depending on the species' habitat needs. Restoration can lead to losses in very species poor areas (*e.g.* deserts) where agricultural expansion has lead to increases in biodiversity; restoring therefore leads to a loss. However, for NNL to be achieved, $\sum_j \sum_s \Delta P_{j,s}$ ensuing from restoration activities must be positive.

The calculation provided in Eq. 3 and Eq. 4 is an approximation, as the marginal persistence changes are determined assuming that each cell is destroyed independently from others, whereas in our simulation more than one cell may be destroyed. The scalability of LIFE scores is discussed by Eyres et al. (2024), and this approximation is not expected to affect the overall conclusions.

LIFE scores intrinsically account for area affected within ΔP.

2.2.3 Species Threat Abatement and Restoration (STAR)

The Species Threat Abatement and Restoration (STAR) approach captures, in two distinct metrics, the potential contribution of threat reduction in remaining natural habitat (STAR_T) and habitat restoration (with threat abatement within the restored habitat) (STAR_R) to the reduction of species extinction risk (Mair et al., 2021). Using STAR_T, a loss can be expressed as:

$$STAR_{loss} = \sum_i \sum_s \sum_t Q_{i,s} W_s C_{s,t} \cdot f_{loss,i} \quad \textbf{\textit{Eq. 5}}$$

where $STAR_{loss}$ is the total loss of dimensionless STAR_T units (>0, dimensionless) including all threats in the different cells i impacted; $Q_{i,s}$ is the current AOH of each species s within cell i (% of global current AOH for s); W_s is the IUCN Red List Category weight of species s (Least Concern = 0, Near threatened = 1, Vulnerable = 2, Endangered = 3, Critically Endangered = 4 (Butchart et al., 2007, 2004)); $C_{s,t}$ is the relative contribution of threat t to species s extinction risk (0-1, dimensionless); and $f_{loss,i}$ is the fraction of cell i where the impact is occurring (0-1, dimensionless).

Although the "full" STAR_R metric assumes abatement for all threats, here we assume, as for MSA, that restoration tackles only threats directly related to land cover, *i.e.*, that would disappear when habitat is restored. Equivalence of losses and gains can then be expressed as $STAR_{gain} = STAR_{loss}$, with:

$$STAR_{gain} = \sum_j \sum_s \sum_{t_{LU}} H_{j,s} W_s C_{s,t_{LU}} M_{j,s} \cdot f_{gain,j} \quad \textbf{Eq. 6}$$

where $STAR_{gain}$ is the total gain of dimensionless STAR$_R$ units (>0, dimensionless); gains occur in cells j; $H_{j,s}$ is the extent of restorable AOH of each species s within cell j (% of global current AOH for s); W_s is the IUCN Red List Category weight of species s (Least Concern = 0, Near threatened = 1, Vulnerable = 2, Endangered = 3, Critically Endangered = 4 (Butchart et al., 2007, 2004)); $C_{s,t_{LU}}$ is the relative contribution of threat t to species s extinction risk, restricted to land cover related threats (0-1, dimensionless, see 2.3.2 for the threats covered); $M_{j,s}$ is a recovery time discount based on the time elapsed since implementation of the restoration actions (10 years in this study, as in (Mair et al., 2021)); and $f_{gain,j}$ is the fraction of restorable area in cell j that is restored (0-1, dimensionless).

STAR scores intrinsically account for area affected within parameters $Q_{i,s}$ and $H_{j,s}$.

2.3 Simulation design and implementation

2.3.1 Experimental design

We develop and implement a global simulation in R (v4.3.3)(R Core Team, 2024), comparing restoration area requirements to achieve NNL for hypothetical biodiversity losses, for each of three biodiversity metrics (MSA, LIFE, STAR). The experimental design is illustrated in Figure 1.

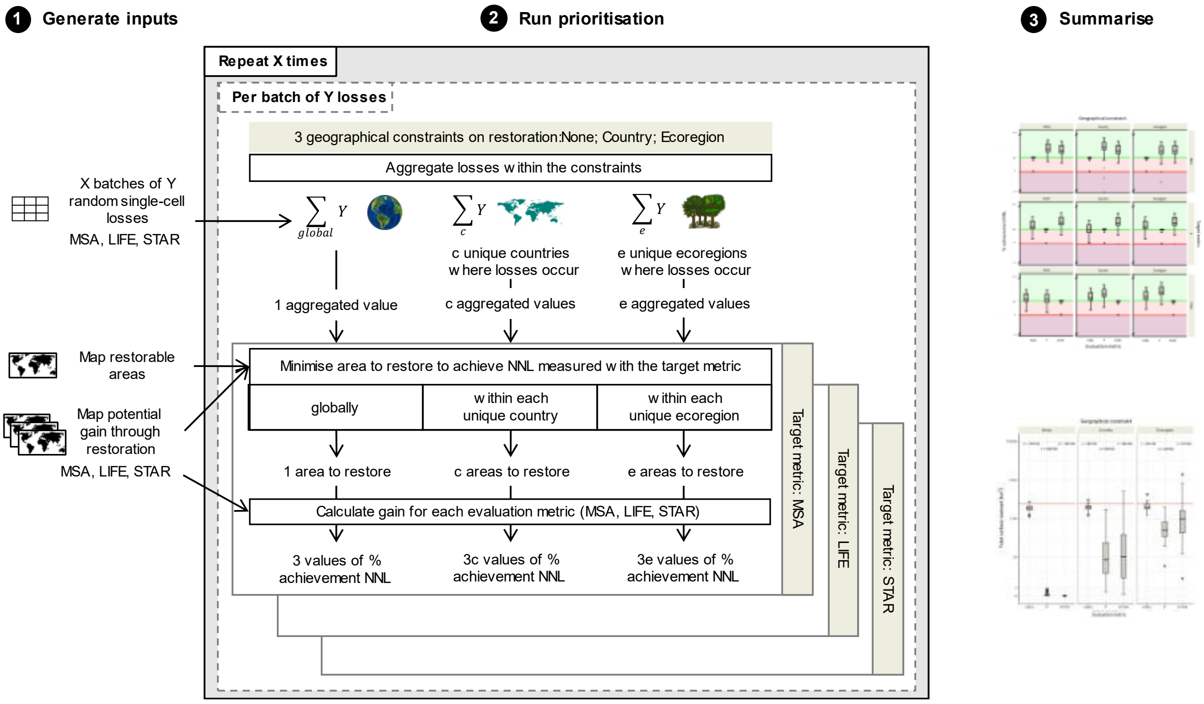

Figure 1. Illustration of the experimental design, to compare restoration requirements to achieve NNL across metrics, for simulated biodiversity loss from corporate activities. The simulation was implemented to run with any number of batches (X) of losses, and any number of losses (Y) within each batch. The target metric is the metric for which NNL is sought. The evaluation metrics are those with which achievement of NNL is computed.

The simulation is designed to replicate any number of corporate loss cases (hereafter referred to as batches) and any number of losses per case. One loss corresponds to the destruction of all the habitat available in a single cell i (*i.e.*, $f_{loss,i} = 1$), chosen at random in the terrestrial realm – as mapped by the three metrics – and without replacement, using the spatSample function from the *terra* package (v1.7-74)(Hijmans, 2024). The magnitude of each loss is calculated as described in Eq. 1 for MSA, in Eq. 3 for LIFE and in Eq. 5 for STAR. In our benchmark case, we simulate 200 batches of 10 random losses, but also perform a sensitivity analysis on both parameters, testing 200 batches of 5 or 20 losses, as well as 100 and 400 batches of 10 losses.

For each batch, an optimisation approach is then used to determine the minimum restorable area to be restored to achieve NNL with respect to the simulated losses measured with each possible target metric (step 2 in Figure 1). Per target metric, the restored area is potentially spread across several cells, which are selected from a global raster of restorable areas, excluding cells where a loss is simulated to occur (losses are assumed irreversible). Three geographical constraints are simulated. In the unconstrained global simulation, the losses are summed to a single global loss value for each batch, and optimisation is performed to determine the minimum area to be restored anywhere globally. For the country and ecoregion constraints, the losses of a given batch are summed per country or ecoregion, and individual optimisations performed to determine, within each country or ecoregion, the required area to restore to achieve NNL. Each optimisation problem is set up using the *prioritizr* package (v8.0.3)(Hanson et al., 2023) and is solved using the Gurobi solver (Gurobi Optimization, LLC, 2023) – further details on parameterisation are provided in Supplementary Material 1. Each solution raster provides the fraction that should be restored per cell to achieve (at least) NNL as measured with the target metric.

2.3.2 Input data collection and processing

We obtained global raster layers of metric values required in calculations of gains and losses from existing data layers. Specifically, we used the global MSA raster layer produced by Schipper et al. (2020) covering mammals, birds and terrestrial plants and aggregated over all pressures included in the underlying GLOBIO model (climate change, land-use, roads, atmospheric nitrogen deposition, hunting), in combination with a raster of cell area produced using the cellSize function in the *terra* package, to compute potential loss of biodiversity in MSA.km² according to Eq. 1. We averaged the global raster layers produced by Schipper et al. (2020) of MSA lost to land-use, for terrestrial plants and warm-blooded vertebrates, and combined the averaged layer with rasters of cell area and restorable proportion in each cell (see below) to compute potential gain of biodiversity in MSA.km² according to Eq. 2. We summed across species groups the global LIFE rasters, under total destruction of existing land cover and when restoring arable or pasture land to natural habitat, produced by Eyres et al. (2024), covering mammals, birds, reptiles and amphibians. We used this habitat destruction map (resp. restoration map) for potential loss (resp. gain) expressed with LIFE according to Eq. 3 (resp. Eq. 4). Finally, we used the global $STAR_T$ raster layer (all threats) and $STAR_R$ raster layer restricted to land cover related threats (based on our expert opinion: threat categories 1, 2.1, 2.2, 2.3, 3.1, 3.2, 5.3, 7.3 and 9.3 in the IUCN Threat Classification Scheme (IUCN, 2023), see Supplementary Material 1), produced by Mair et al. (2021), covering mammals, birds and amphibians, for potential loss and gain values expressed with STAR as in Eq. 5 and Eq. 6. A comparison of the scopes of the three metrics and their underlying data sources is provided in Table S1 (Supplementary Material 1).

We used the raster layer representing the maximum proportion (0-1) of terrestrial areas currently used for crops or pasture that are available for restoration, from (Strassburg et al., 2020). We aligned the coordinate reference system and resolution of all other maps to those of this map of restorable area (Mollweide, 4.96×4.96 km). The cell size for the simulation is therefore 4.96×4.96 km. For construction of the map of potential gain expressed with LIFE, this harmonization requires the use of the original raster of restorable area used by Eyres et al. (2024) – please refer to the code provided for further details. The common extent between the map of restorable area and global vector layers of country and ecoregion boundaries by the World Bank (2020) and Dinerstein et al. (2017) is used to determine the final extent of all raster layers used in the simulation ($x_{min} = -17702327$, $x_{max} = 17876233$, $y_{min} = -6826244$, $y_{max} = 8750095$). The vector layers are rasterised to produce rasters containing the country/ecoregion in which each cell lies (fully or the majority of it).

In the simulation, we only consider cells that have data in all raster layers (map of restorable area, country/ecoregion per cell, metric-specific maps of potential loss and gain) – cells with *NA* values (no data) occur for example for oceans or water bodies. For each optimisation, the planning unit object contains restorable area in km² per cell. The target metric map of potential gain is used as the features object. For optimisations under country/ecoregion constraints, the maps of restorable area and potential gain expressed with the target metric are cropped to the appropriate geographical conditions using the country/ecoregion rasters before use.

2.3.3 *Analysis of the outputs*

The total gain from the set of restorations resulting from the optimization problem is calculated as in Eq. 2, Eq. 4 and Eq. 6 with $f_{gain,j}$ provided in each solution raster. The gain is compared to the absolute value of the loss (both expressed with the evaluation metric), to determine the percentage achievement of NNL for each possible combination of a constraint, target metric and evaluation metric. In our benchmark simulation with 200 batches of 10 simulated losses, under the global constraint, this yields 200 data points per combination of a target and evaluation metric, since the 10 losses in each batch are summed to a single overall loss. Under the country and ecoregion constraints, this yields a number of data points equal to the number of unique countries or ecoregions per batch – up to 2000 if all 10 losses occur in unique countries or ecoregions for all 200 batches.

Data points corresponding to both a loss and gain of 0 are coerced to 100 % achievement of NNL. When none of the cells within the geographical constraint contain restorable area, the gain and area restored are coerced to 0 (and no optimisation performed). When the optimisation fails because the target (*i.e.* achievement of 100 % NNL for the target metric) cannot be met, a solution raster is manually created by designating for full restoration all cells, available for restoration, that have a potential gain through restoration greater than 0, as measured with the target metric. This leads to partial achievement of NNL for the target metric.

The total area restored is also calculated per batch for each possible geographical constraint and target metric, in the cases where NNL is consistently 100 % achieved within the batch. We choose to only represent cases with consistent 100% achievement of NNL in a batch for the target metric, to ensure comparability between batches – a smaller area restored compared to the others could otherwise be due for example to few cells being available for restoration, leading to underachievement of NNL.

3. Results

3.1 Percentage achievement of NNL

Our simulations reveal that achieving NNL for one metric does not guarantee this for the other two (Figure 2, Table 1). Under the global constraint, the restoration requirement to achieve NNL with MSA as the target metric leads in the majority of cases to overachievement of NNL as measured with LIFE and STAR. As the geographical constraint is increased to country then ecoregion, the overall performance for NNL gets worse (Table 1). When achievement of NNL is defined with respect to either LIFE or STAR as target metrics, the median percentage achievement of NNL is consistently below 100 % for the other two evaluation metrics (MSA and STAR, MSA and LIFE, respectively). Under increasing geographical constraints, this failure to achieve NNL is slightly mitigated (Table 1), but whatever the target metric for NNL, it is not consistently achieved for the other two metrics. The sensitivity analysis suggests that the results are robust to changes in batch number/number of losses, which affect the number of outliers but not the general shape of the box plots (Figures S1, S3, S5 and S7, Supplementary Material 2).

We observe cases where the simulation does not achieve NNL for the target metric. The corresponding data points lie at 0 %, or between 0 and 100 % achievement of NNL for identical target and evaluation metric pairs (Figure 2). They reflect situations when there is no or not enough restorable area or potential gain, respectively, in the geographical constraint's perimeter, occurring much more frequently (8.1-10.6 % of cases) under the ecoregion – especially in tundra, taiga, desert and shrubland/grassland ecoregions – than the country constraint (Table 2; these countries/ecoregions are listed in Tables S2 and S3 in Supplementary Material 2). Points at 0 % due to no potential gain occur only for LIFE, where the values of potential gain through restoration are based on scores provided in Eyres et al. (2024), obtained using a different map of restorable AOH than the one used in this study. For MSA under the country constraint, there are many more data points at 0 % achievement NNL than for LIFE and STAR. These all occur in Greenland, where losses for LIFE and STAR metrics are mostly measured at 0 and have thus been coerced to 100 % achievement of NNL (see Methods section 2.3.3).

Table 1. Summary of the median percentage achievement of NNL per case represented in Figure 2.

Evaluation metric	MSA			LIFE			STAR		
Target metric / Geographical constraint	None	Country	Ecoregion	None	Country	Ecoregion	None	Country	Ecoregion
MSA	100	100	100	1.14E+03	214	89.0	248	63.3	28.4
LIFE	6.59E-03	0.151	1.15	100	100	100	6.59E-03	0.151	1.15
STAR	3.65E-04	5.93E-03	0.393	8.63E-06	0.0471	0.917	100	100	100

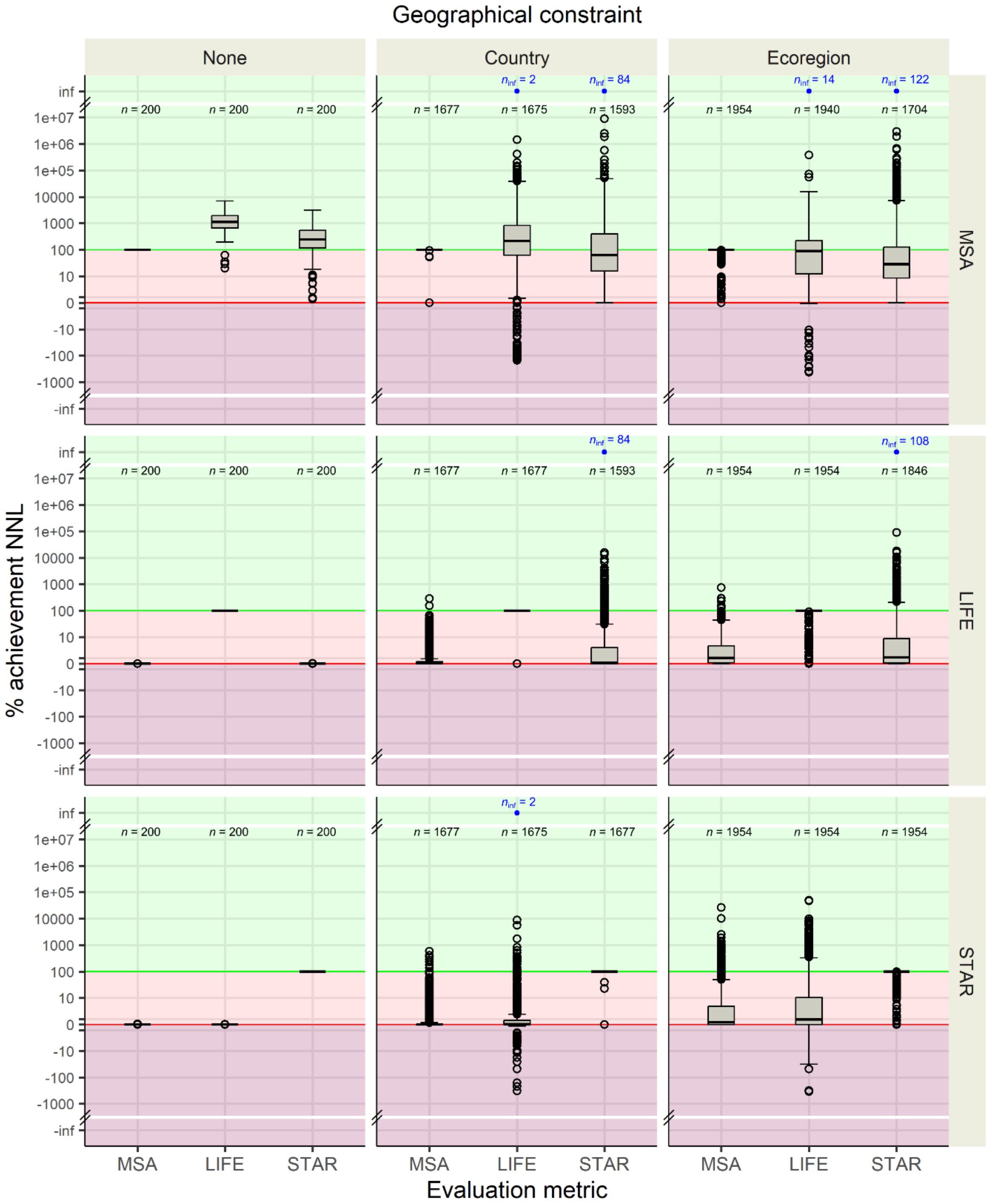

Figure 2. Percentage achievement of NNL expressed per evaluation metric, depending on the target metric and geographical constraint. None: per batch, the losses were summed, and optimisation performed to determine the restored area anywhere globally. Country/Ecoregion: per batch, the losses were summed within each unique country/ecoregion and individual optimisations performed to determine, within each country and ecoregion, the required area to restore. n = number of data points contributing to the boxplots. n_{inf} = number of data points at infinity (no loss as measured with the evaluation metric), represented for visualisation but not contributing to the boxplots. Hollow points represent outliers (included in the box plots) and blue points represent infinite values (not included in the boxplots). The box delineates the 1st and 3rd quartiles, and the median. The bottom and top whiskers extend to the data point that are at most at a distance of 1.5 times the interquartile range from the bottom or top hinge, respectively. Green (100 %) and red lines (0%) indicate NNL and a net loss equal to the initial loss,

respectively. Green, red and purple shading indicate a net gain, a net loss smaller than the initial loss, and a net loss greater than the initial loss, respectively.

Table 2. Summary of the number of data points in Figure 2 for which there is 0 % or strictly between 0 and 100 % achievement of NNL for the target metric. *n* = number of data points contributing to the boxplots. n_0, $n_{partial}$ = number of data points (included in the total *n*) for which there was 0 % or strictly between 0 and 100 % achievement of NNL for the target metric, respectively. In brackets: the proportion (%) of *n* that this represents. For LIFE, n_0 is split between points for which the cause is no restorable area (73 points) or insufficient potential gain (44 points).

Target metric = Evaluation metric	MSA		LIFE		STAR	
Geographical constraint	Country	Ecoregion	Country	Ecoregion	Country	Ecoregion
n	1677	1954	1677	1954	1677	1954
n_0	20 (1.2 %)	76 (3.9 %)	4 (0.24 %)	73 + 44 (6.0 %)	1 (0.060 %)	76 (3.9 %)
$n_{partial}$	3 (0.18 %)	100 (5.1 %)	0 (0 %)	90 (4.6 %)	2 (0.12 %)	83 (4.2 %)

When the target and evaluation metric differ, we observe some data points at 0 % achievement of NNL as measured with the evaluation metric (Figure 2). These occur either when (a) there is no restorable area within the constraints perimeter despite a loss measured with the evaluation metric; (b) there is no gain as measured with the evaluation metric; or (c) when there is no loss as measured with the target metric, *i.e.*, the randomly chosen cell in which the loss occurs has a value of 0 for the target metric, so nothing needs to be restored, but the loss is greater than 0 for the evaluation metric. When LIFE is the evaluation metric (but not for MSA or STAR), restoration can occasionally lead to losses, because the restored habitat is unsuitable for one or more species that have thrived in a human modified habitat. This results in a percentage achievement of NNL below 0 (Figure 2), *i.e.*, a net loss of biodiversity that is greater than the initial loss simulated.

3.2 Area restored to achieve NNL

Across all three geographical constraints tested, NNL is overall achieved at the batch level with a smaller median area restored (in km²) when the target metric driving the restoration prioritisation is LIFE or STAR, rather than MSA (Figure 3). For both the LIFE and STAR metrics, adding a geographical constraint substantially increases both the median area restored to achieve NNL across the entire batch of losses, and the overall spread of areas restored (Figure 3). Median restored area is around an order of magnitude greater for the ecoregion than the country constraint. The ecoregion constraint also drastically reduces the number of batches within which NNL is consistently achieved (see sample sizes in Figure 3). For MSA, the geographical constraints only slightly increase the median area restored and do not seem to affect the spread of areas restored across the different batches. The red dashed line in Figure 3 represents the maximum total area of habitat destroyed per batch (number of losses per batch multiplied by cell area). The area effectively destroyed per batch is likely smaller than this maximum value. Across all three constraints, the median area restored when MSA is the target metric is of the same order of magnitude as the maximum possible area lost. For LIFE and STAR, it is consistently smaller. As for the percentage achievement of NNL, the results appear robust to changes in batch number/number of losses, with the same general trends and spreads (Supplementary Material 2: Figures S2, S4, S6 and S8).

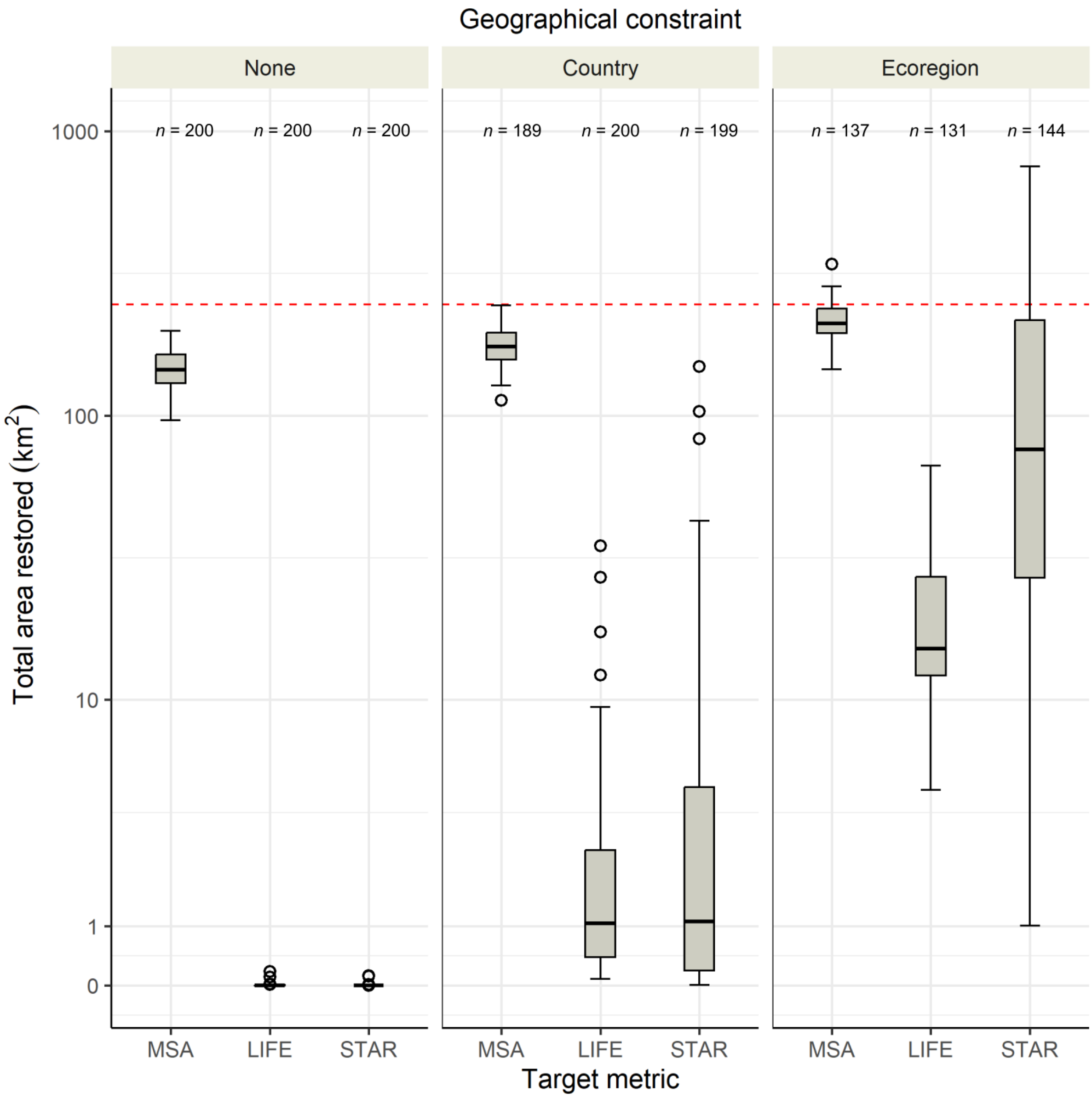

Figure 3. Total area restored per batch, target metric and geographical constraint, for 200 batches of 10 losses, in the cases where NNL is consistently 100 % achieved within the batch (with the relevant grouping from the constraint). None: per batch, the losses were summed, and optimisation performed to determine the restored area anywhere globally. Country/Ecoregion: per batch, the losses were summed within each unique country/ecoregion and individual optimisations performed to determine, within each country and ecoregion, the required area to restore. *n* = number of batches where NNL is 100 % achieved for all losses, i.e., number of data points contributing to the box plot. The horizontal dashed red line indicates the maximum total area destroyed per batch. The box delineates the 1st and 3rd quartiles, and the median. The bottom and top whiskers extend to the data point that is at most at a distance of 1.5 times the interquartile range from the bottom or top hinge, respectively.

4. Discussion

4.1 Result drivers

When MSA is the target metric the overall performance for NNL for LIFE and STAR evaluation metrics worsens with increasing geographic constraints, but the reverse (although small) effect is observed when LIFE or STAR are the target metric. We also observed that under the global constraint, the area restored is much larger for simulations with MSA as the target metric, than those using LIFE or STAR as a target metric. These results are driven by the nature of the metrics and of the optimisation, which determines the smallest possible area to restore. LIFE and STAR gain values have a much larger distribution compared to MSA: the value of the 95th percentile of potential gain for MSA is approximately five times greater than the median, while for LIFE and STAR it is close to 40 and 140 times the median, respectively (Figure S9, Supplementary Material 3). This stems from the different components of nature that the metrics measure. MSA is an ecosystem condition metric, looking at local ('alpha') species diversity within any particular ecosystem, while LIFE and STAR are influenced by the highly skewed overall geographical distributions of individual species. For MSA, cells for restoration selected first (*i.e.*, with the greatest potential gain through restoration) are those with very little remaining biodiversity, where land-use has been the dominant source of biodiversity loss and where most/all of the cell is restorable. For LIFE and STAR, potential gains from restoration can take extreme values in cells that are within the former AOH of one or more species with a very small global area of current AOH. These extreme high-value cells occur in only a few places. As the scale is reduced to country and further to ecoregion, fewer very high-value cells are available (Figure S10, Supplementary Material 3). It appears from the results that the cells that have highest MSA potential gain globally also happen to have unusually high LIFE/STAR potential gain values, while this relationship is weaker for country and ecoregion scales. When the target metric is LIFE or STAR, increasing geographic constraint means that there are fewer cells with high values available for restoration, so a larger overall area needs to be restored, which in turn will generally increase the gains expressed in MSA.km².

4.2 <u>Implications for the use of complementary biodiversity metrics</u>

Our results highlight the challenges in choosing and applying appropriate currencies for biodiversity compensation (Mayfield et al., 2022), and the importance of understanding clearly what metrics actually measure and how. In the specific case of offsetting, it is unlikely that MSA would be used as an assessment metric for direct-operations offsets, despite its relevance for measuring ecosystem condition, as it cannot easily be measured in-field, requiring extensive ecological surveys (CDC Biodiversité, 2020). STAR has been proposed (but not yet used) as an offset metric (IBAT, 2021), focusing on priority features. This requires use of field-collected data to calibrate estimated values and assess realized gains (Mair et al., in prep.) – the same would be needed for LIFE to be used as an offset metric. For the less well-defined impacts occurring in value-chains however, it is more likely that business and finance will be looking to metrics such as MSA, STAR and LIFE for assessing both potential losses and gains. MSA and STAR are already in use for corporate impact measurement (CDC Biodiversité, 2023), and recommended by the TNFD and the GBF (see section 1. Introduction).

From the analysis performed here, overall outcomes for biodiversity will be more satisfactory if using two or more complementary metrics – MSA and STAR and/or LIFE – for value-chain level NNL assessments. Indeed, a single metric alone does not guarantee NNL in biodiversity: loss in another dimension of biodiversity that is not measured by the single indicator could still occur, or gains in one biodiversity dimension may not equate to gains in another. Comparing the Biodiversity Habitat Index (BHI) and the Red List Index (RLI) across ecoregions globally, Stevenson et al. (2024) also found some disagreement between BHI and RLI, with a number of ecoregions showing high BHI and low RLI scores, or the reverse. These metrics are conceptually similar respectively to MSA, and LIFE and STAR, although their application is at large geographical scales, and BHI focuses on gamma diversity, contrary to MSA. Our findings specifically reinforce the previously highlighted complementarity between an approach based on ecosystem condition, measured for example by MSA which reports changes in alpha diversity at a local scale, and one based on species extinction risk like STAR or LIFE, reporting changes in gamma diversity, for assessment of corporate impact risks and opportunities (Hawkins et al., 2023). Two main approaches could be used: dimensioning compensation to ensure NNL as measured by both (or all three) metrics, or using STAR/LIFE as a significance weighting for MSA in calculating impacts. The former is likely to be more demanding in terms of overall compensation requirements; the latter is more likely to focus investment in the most important locations for biodiversity in terms of species persistence.

In either case, consideration should be given to the appropriate scale of fungibility for gains and losses. Global fungibility could involve compensation for potentially very different biodiversity features than those that are impacted. Country or ecoregion-level are candidate geographical units for bounding loss/gain assessments, large enough to allow some flexibility, but relatively coherent in terms of socio-economic or ecological characteristics, respectively. These could also help support linkage of offsetting outcomes to jurisdictional biodiversity targets, aligned with GBF goals (Simmonds et al., 2020). We observed that adding such spatial scale constraints led to several instances where NNL could not be achieved for the chosen target metric. This highlights the imperative to carefully consider locations of corporate activities; NNL could be impossible to achieve depending on where losses occur. Following the mitigation hierarchy at the level of value chain impacts (Maron et al., 2023) should ensure that these situations are properly evaluated and any losses avoided or reduced if possible. These constraints also did not align achievement of NNL across the three metrics. Stricter equivalence rules, for example on the ecosystem type, landscape and species lost, could also allow better alignment of the outcomes. This could also avoid the risks associated with measuring NNL with any of these metrics in coarse ways, such as compensating for the potential extinction of a species by restoring habitat of other threatened species. While both of these outcomes are comparable in a metric, there is in reality no offset for extinction. Such strict equivalence rules would however be challenging to implement for real-world value chain impacts, since their exact location is likely unknown, for those occurring higher up in the chain in particular. Using country ecoregion components (the portions of ecoregions within a particular country) as a default geographical unit could be a practical approach, providing relatively high socio-economic and ecological coherence together with a degree of flexibility.

Our aim was not to comment on the relative merits of the three biodiversity metrics studied, or present one as superior to the others. We highlight their main limitations in Supplementary Material 3, to further discourage such interpretation of these results. By design, there are a number of components of biodiversity that they do not capture; this cannot be considered as a limitation of the metrics themselves. These include genetic and phylogenetic diversity, functional integrity and diversity, and ecosystem services, among many (Convention on Biological Diversity, 2022; Gardner et al., 2013; Richardson et al., 2023). Aiming for NNL with respect to all such components would be ideal, but generally impractical. This study highlights the challenges of choosing which few proxy measures can feasibly be assessed and used in a simplified framework for biodiversity compensation.

4.3 Outlook and future work

While the three metrics conceptually cover biodiversity from all taxonomic groups, the available data layers expressing global biodiversity state with each metric have limited coverage to date. In this study, all three data layers used cover mammals and birds, with the MSA data also covering terrestrial plants, LIFE amphibians and reptiles, and STAR amphibians; these characteristics are susceptible to change as the data layers are updated, and could influence the magnitude of gains and losses. For instance, terrestrial plant data are not yet available globally for STAR, however using the metric at the national level Mair et al. (2023) found that $STAR_T$ values for plants were 30 times those for vertebrates in their case study in South Africa. As updated values become available for the metrics across taxa, applying the framework for each species group – for LIFE and STAR, as this is not possible for MSA – could provide refinements to the results presented here. Indeed, Eyres et al. (2024) observed some regional differences in the effect of habitat degradation and restoration for amphibians and reptiles. It should be noted that the metrics differ also in their approach to land cover mapping (see Table S1, Supplementary Material 1). Former AOH for STAR and LIFE also use different timeframes, and LIFE covers all species in the taxon groups included, while STAR covers only threatened and near-threatened species. We expect that these factors influence the results much less substantially than differences in overall skew of potential gain values discussed in section 4.1.

Assumptions were made for the simulation of the losses and restoration actions. Regarding the losses, corporate activities were assumed to totally destroy the habitat at the location of impact, to allow comparability across the three metrics studied. Losses could however be calculated outside of this assumption: MSA_i in Eq. 1 would no longer be the biodiversity state prior to habitat destruction (entirely lost), but equal to the difference between the biodiversity state before and after negative impacts on biodiversity (some biodiversity could remain despite corporate activities). The global data layer for MSA already includes broad levels of intensity for the different pressures, allowing the measure of changes in management practices. For LIFE scores, alternative habitat destruction scenarios could be defined and computed, such as conversion of habitats and pastures to arable land, as in (Eyres et al., 2024). Such scenarios would be more challenging to compute for STAR, but could potentially be achieved through only taking into account certain threats in Eq. 5. For both LIFE and STAR, another approach for refinement could be to weight different habitats/land-use types by their suitability for each species. This could be explored in future work. In the context of corporate impact minimisation, increasing the ability of these metrics to capture nuanced changes in management practices, as opposed to only the effects of drastic actions, should be a research priority.

Regarding restoration, it was assumed to only change land cover, as it is likely that restored habitat can still undergo the effects of other pressures, such as nitrogen deposition, if it is close to agricultural land for example, or climate change. We did not investigate restoration actions that could reduce the impact of these pressures, which could be accounted for with MSA and STAR, since the most recent global MSA values cover the impact of climate change, land-use, roads, atmospheric nitrogen deposition and hunting (Schipper et al., 2020), and STAR covers IUCN Red List threats (Mair et al., 2021). LIFE accounts for changes in AOH only, so this could not be tested (Eyres et al., 2024). It should also be noted that LIFE and STAR account for changes in AOH without considering how fragmented the total AOH may be. Since the probability of impact of a given threat on biodiversity is unequally distributed globally (Harfoot et al., 2021), we expect that including other threats could affect the results presented here.

Furthermore, our framework determines the restoration requirement by minimising the overall area to restore. Realistically, the choice of restoration locations is also likely influenced by economic considerations within the company of concern, since cost-effectiveness is an important consideration when selecting corporate impact mitigation actions (White et al., 2023). Future work could include the use of opportunity cost data to construct the planning units, comparing the outcomes to those based on area. As areas with lower costs of restoration are likely to be the ones with lower potential gain through restoration (Strassburg et al., 2020), this question raises interesting issues regarding the trade-off between restoration areas and costs.

Finally, the potential gain from restoration will likely materialise a long time in the future, and is a maximum potentially attainable gain (or loss in some cases with LIFE scores). This time lag and the uncertainty of biodiversity recovery following a release in anthropogenic pressures or restoration (Jones et al., 2018; Maron et al., 2012; Quétier and Lavorel, 2011; Schipper et al., 2016) should be addressed when designing offsets for given losses of biodiversity, as stressed in Eyres et al. (2024). Regarding temporality, the gain expressed with MSA and LIFE could be discounted in the same way as STAR based on a defined time-frame for restoration (10 years in this study, resulting in a weighting of 0.29 for parameter $M_{j,s}$ in Eq. 6 (Mair et al., 2021)). This would be expected to increase the area required to achieve NNL for both of these target metrics. Regarding the uncertainty of biodiversity recovery, Mair et al. (2021) use results presented in (Jones et al., 2018) to parameterise the temporal factor $M_{j,s}$ in Eq. 6. Jones et al. (2018) also evaluate the extent of ecosystem recovery for different ecosystems under various disturbance types; gains expressed in Eq. 2, Eq. 4 and Eq. 6 could be corrected using factors derived from these results, to account for the expected incomplete ecosystem recovery. Calibration of the global datasets with information from the ground will also be necessary. For LIFE and STAR, this would include an evaluation of the feasibility of species recolonising restored habitat. Overall, the uncertainty of restoration outcomes further supports the strict application of the mitigation hierarchy regarding corporate impacts, as mentioned above: minimising impacts will reduce the reliance on uncertain restoration outcomes in corporate NNL journeys.

5. Conclusion

The goal of the present framework is not to inform exact restoration requirements or justify the adequacy of a specific NNL policy. We discourage the use of it as such, as these requirements would necessarily be inaccurate, considering the use of global datasets for the three metrics, involving modelling and simplifications on the basis of assumptions presented above. Field-verification would be crucial to obtain specific measurements and calculate satisfactory restoration requirements if applied to real corporate losses of biodiversity. This study uses restoration as an illustration of how three metrics – MSA, LIFE and STAR – compare with respect to evaluating NNL. We illustrate that achieving NNL for a single biodiversity indicator does not guarantee NNL for indicators that address other dimensions of biodiversity. Considering the wealth of biodiversity impact metrics available and the momentum around concepts of NNL in the corporate sphere, our results are cause for caution in the use of these metrics. Although it is unfeasible to consider a large number of different indicators, corporates should carefully choose a set of metrics that represents the biodiversity components relevant to their activity, and aim for NNL with respect to this selected set, as opposed to a single metric.

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7. Conflict of interest

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