Evaluating Biodiversity Credits Using Metacommunity Modelling

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Open Research statement:

This submission uses novel code, which is provided, per our requirements, in an external repository to be evaluated during the peer review process via the following link: https://github.com/maczik/biodiversity_credit_model

Keywords:

biodiversity credits, biodiversity metrics, mean species abundance, Living Planet Index, nature positive, metacommunity models.

Abstract

Enhancing global biodiversity is one of the key pillars of the UN's Sustainable Development Goals, widely acknowledged as necessary to mitigate climate change. Nevertheless, an annual additional of US$ 700 billions of funding is required to reach the '30 by 30' target set out in the Kunming-Montreal Global Biodiversity Framework. The proposed voluntary biodiversity credit market aims to bridge this funding gap via a market-based mechanism by assigning financial value to biodiversity and ecosystem services. To capitalise on this nascent market, several voluntary biodiversity credits are emerging from independent start-ups, internationally respected NGOs, and established carbon credit companies. Projects which are primary funded by credit sales must align their objectives with their credit issuance methodology to avoid underdelivering on their commitments. In this pioneering study, the differences in behaviour between six different well-established credits were investigated, to highlight the impact of methodology choice and evaluate their accuracy on representing ecosystem level changes. Our results indicate that all six credits are suitable for tracking basic restoration efforts, however there are significant differences in their methodologies and thus their responsiveness to interventions. Furthermore, not one credit was suitable to successfully track all six distinct nature-positive or nature-loss experiments simulated, suggesting that a universal biodiversity credit remains unattainable.

1. Background

A global increase in biodiversity is one of the key pillars of the UN's Sustainable Development Goals. Enhancing biodiversity has been shown to combat desertification and halt land degradation, provide disaster protection, and play a pivotal role in achieving the 1.5°C temperature increase limit set by the Paris Agreement in 2016 (1-4). Nonetheless, current anthropogenic vertebrate species loss is 100 times above the natural rate, which is widely considered a sixth mass extinction event (5). Any climate adaptation strategy must place healthy ecosystems and rising biodiversity at its core since they are vital for carbon storage, mitigating extreme weather events, and preventing coastal erosion (2, 4, 6-9). Conversely, climate change is the most significant driver of global biodiversity loss, with the latest IPCC report indicating substantial damages and irreversible losses to the biosphere (10-12). Thus, in parallel to an energy transition, a 'biodiversity' or 'nature' transition is also essential for a sustainable future (13). Accordingly, the historic 2022 Kunming-Montreal Global Biodiversity Framework was established to reduce threats to biodiversity, via halting extinctions, preservation of 30% of the planet's terrestrial and marine ecosystems by the year 2030 and restoration of 30% of all degraded ecosystems by 2030 (14).

Resource constraints are frequently cited as barriers for the limited progress towards achieving biodiversity targets (15, 16). Public investments in biodiversity amount to approximately US$ 121 billion, constituting only 0.19–0.25% of global GDP (17), while the annual global finance gap is estimated between US$ 598 and US$ 824 billion (15). Over the past decades, private conservation finance mechanisms have not been sufficient in

scale or speed to address the biodiversity funding gap (15, 18). This is particularly concerning given that over half of the world's GDP, approximately $40 trillion, is either moderately or highly reliant on nature and ecosystem services (19, 20). Consequently, beyond merely addressing the funding gap, a transformative shift is necessary to tackle the underlying drivers of biodiversity loss (21-23).

Several international initiatives have been established to facilitate this shift. The UNDP's BIOFIN program supports the development of national biodiversity finance frameworks and provides guidance on bridging national finance gaps for biodiversity conservation in 31 developing countries (24). Additionally, the Taskforce on Nature-related Financial Disclosures (TNFD) has been established as a voluntary initiative aimed at formulating guidelines for corporations to disclose information that assists investors, lenders, and insurance companies in evaluating and pricing nature-related risks. TNFD reports have highlighted the necessity for a comprehensive framework to redirect private investment from nature-negative to nature-positive outcomes, emphasizing the importance of developing metrics, targets, and risk management strategies. Measuring biodiversity and therefore estimating the value change achieved by conservation and restoration projects remains a key challenge in the sector (25). While species richness is considered the fundamental metric for capturing the diversity of a community it is often combined with additional metrics such as taxa, functional types, or genetic distance to capture habitat and ecosystem level trends.

In face of growing interest in nature-positive projects, fledgling biodiversity credit market is emerging to address this issue. Analogous to the more well-established carbon market,

biodiversity credit or nature credit markets aim to establish a market-based mechanism by assigning financial value to biodiversity and ecosystem services. Thus, the credits have inherent value, and can be traded on the market, allowing companies to specialise to different segments of the value chain. Project developers undertake conservation or restoration efforts, generating credits that are certified by standards bodies such as Verra and ERS before being connected to investors.

The market-based nature of this sector has led to a proliferation of voluntary biodiversity credits from various sources, including start-ups, NGOs, and established carbon credit companies. Many metrics aim for a broad assessment of biodiversity, while others focus on specific aspects of conservation and restoration for instance extinction risk. Figure 1 displays the variety of credits available, organised by their range of focus. While some credits are calculated using a combination of species abundance data, others use additional indicators from the habitat and ecosystem levels. Importantly, there is no company which equally focuses on all three aspects. The diversity of credits presents a challenge in selecting the most appropriate one, for a given project, considering their differing focuses and methodologies. Crucially, as credit sales are the primary source of funding for voluntary nature-positive projects, it is critical that credit issuance accurately represent the aims and achievements of the project. Misalignment can lead to undervaluing the achieved results, or underdelivering on the promised environmental uplift. Due to the nascent nature of this field no previous academic studies have attempted to shed light on this issue. This study investigates the difference in responses of six well-established credits to assess the impact of methodology choice and evaluate their accuracy in representing ecosystem-level changes.

2. Methodology

To understand credit responses to interventions large scale computational simulations of complex ecological assemblages have been employed, utilising the Lotka-Volterra Metacommunity Model (LVMCM). This established, spatially explicit, multi-layered metacommunity simulation model can reproduce a variety of macro-ecological patterns, including recreating occupancy frequency distributions or strongly right-skewed range size distribution (26-28). For a further detailed description of the LVMCM please refer to the Appendix. In our study, the LVMCM was adapted to track numerous biological indicators, established international biodiversity metrics and voluntary biodiversity credits, while simulating various experiments. The simulation process begins by setting up an environmentally heterogeneous, spatially explicit abiotic landscape, followed by the assembly of a spatially explicit, macro-ecologically accurate community, by the gradual invasion of species with randomly generated traits. Afterwards, the community dynamics are simulated throughout environmental degradation and restoration events, while basic biological data is measured at each stage. This data is used to calculate biodiversity metrics and estimate biodiversity credits and their change over time.

Following a comprehensive review of 35 biodiversity credit issuers and nature-positive project developers, six distinct credits were selected for integration into the LVMCM, prioritizing feasibility of implementation. The LVMCM tracks species in different environmental and spatial settings, therefore calculating credits and metrics that use raw biological data is relatively easy. The LVMCM is not suitable for credits that depend on

expert assessments. As voluntary biodiversity credits are a novel product in a nascent market, the availability of methodology papers also posed challenges. Finally, special care was taken to ensure that the chosen credits are representative of a variety of fundamentally different methodologies. As Figure 1 indicates, *Botanic Gardens Conservation International's Biodiversity Impact Credits* and *Savimbo's Biodiversity Credit* rely on only species level data, *BioCarbon Registry's Biodiversity Credit* and *The Wallacea Trust's Biodiversity Credit* require both species and habitat-based markers, while *Verra's Nature Credit* and the *Organisation for Biodiversity Certificates' Biodiversity Index* focus primarily on ecosystem-wide data. Several of these credits can be defined within the model either directly or with minor modifications. For the scope of this paper, credit issuers' methodologies to calculate biodiversity is investigated. Therefore, the metrics modelled do not account for additional modifications to compute the final credits, such as accounting for leakage or a buffer. Innovative solutions needed to be used to model indicator species, the IUCN Red List, and the IUCN Red List of Ecosystems (29-31). Furthermore, to help the contextualisation of the credits modelled, several established and independent biological metrics have also been implemented in the LVMCM. These are overall biomass, species richness, Range Size Rarity, Living Planet Index, Mean Species Abundance, and the Species Threat Abatement and Restoration Metric (STAR) (32-35). A detailed explanation of the methodology for implementing credits and metrics can be found in the Appendix.

3. Results and Discussion

This study aims to analyse the behaviour of six different voluntary biodiversity credits in a variety of simulated nature degradation and restoration experiments. The experiments were conducted after assembling a macro-ecologically representative metacommunity over a spatially explicit 10 by 10 grid of sites with varying environmental conditions. For all experiments, apart from the *Project Area Increase*, modifications have been made to the entire grid. The detailed results are presented in Table 1, with the interpretation of a metric's suitability for a given experiment showcased in Table 2.

3.1 Environmental Degradation Experiment

Within the LVMCM species are affected by their environments through their intrinsic growth rates, which are determined by a species' intrinsic traits and the local environment. To model general environmental degradation within a patch, all species' growth rates were gradually reduced, up to the extinction of all species. Nearly all metrics successfully indicated the degradation event taking place and distinguished between the severity of the degradations. Notably, however, *The Wallacea Trust's Biodiversity Credit* does not show negative results. The Biodiversity Credit's methodology uses a strict thresholding-based methodology to categorise continuous data into five steps between the degraded to the reference state. Perhaps, these thresholds are not sensitive enough to pick up the intricate negative changes in the ecosystem.

3.2 Environmental Restoration Experiment

Environmental restoration requires a degraded environment. Therefore, after the initial assembly of the metacommunity a degradation event was modelled as above described followed by a full restoration. Most metrics and all credits were adept for monitoring the outcomes of environmental restoration, aligning with the primary objective of these credits. For most metrics a sharp decrease is visible on the final, most severe degradation event was attempted to be restored. This is because at during such an extreme degradation event most of the species went extinct and thus a full restoration was not possible. Unsurprisingly, the number of extinctions parameter was not suitable for assessing restoration, as there are no mechanisms for re-establishing lost species within the LVMCM.

3.3 Large Extinction Event

A large extinction episode was modelled by removing an increasing number of species from the assembled community. This frequently resulted in secondary and tertiary extinctions but freed up new niches for the remaining species to occupy. Again, most metrics and credits correctly represented the negative change in the health of the metacommunity. Notably, biomass remained unchanged, as the remaining species filled the newly vacated niches post-extinction. Similarly to the environmental

degradation experiment, *The Wallacea Trust's Biodiversity Credit* is not suitable for representing the extinction, as its thresholding system might not pick up the scale of changes simulated.

3.4 Project Area Increase

Most biodiversity credits, including 5 out of the 6 examined here, are calculated as a product of project area size and a factor computed from various biodiversity metrics. However, the emphasis on the project area varies between methodologies. To quantify the role of area, the restoration of progressively increasing project area was modelled to understand the credit's behaviour. Experimental results are compared against a control experiment where the same sized degraded environment is not restored but is assessed. The findings indicate that all credits and metrics, except for the number of extinctions, can reflect the positive effects of a larger restoration effort. Remarkably, metrics and credits not directly tied to project area size, such as biomass, the Living Planet Index, or the Biodiversity Impact Credit from Botanic Gardens International, also show significant increases with larger restoration projects. Interestingly, some credits exhibit a completely linear increase with project size (e.g. *Organisation for Biodiversity Certificates' Biodiversity Index* and *The Wallacea Trust's Biodiversity Credit*), while others reward larger restoration efforts overproportionally (e. g. *Savimbo's Biodiversity*). The response of *Verra's Nature Credit* depends on the baseline trend allocated to a given location. This paper investigates biodiversity metrics and does not account for additional modifications, such as accounting for leakage or a buffer. Therefore, a neutral

baseline trend allocation was used for the simulations, nonetheless a negative baseline trend allocation would result in a non-linear increase.

3.5 Species-specific Restoration Experiment

Field restoration efforts often focus on a single species that is threatened or of ecological or sentimental significance (36-38). This experiment investigates how metrics responded in the face of such changes. In the LVMCM, after an initial desaturation of the assembled community, the rarest species was targeted by progressively increasing its growth rate. It is expected that minor changes will benefit the entire community; however, above a certain threshold, the targeted species may adversely affect other species, resulting in an overall detrimental impact on the community. Remarkably, only two of the modelled metrics successfully reproduced this pattern: *Botanic Gardens International's Biodiversity Impact Credits* and *Savimbo's Voluntary Biodiversity Credits*. Crucially, the expected pattern is produced by the median of the *Botanic Gardens International's Biodiversity Impact Credits* while the mean of *Savimbo's Voluntary Biodiversity Credits*. In the latter's case the pattern is created by the outsized impact of a handful of outliers, where the selected indicator species coincided with the species targeted for restoration. Therefore for reliable results for a single run both the targeted and several vulnerable species need to be tracked for *Savimbo's Voluntary Biodiversity Credits*.

Some credits did not register a change at all (e.g. *BioCarbon Registry's Biodiversity Credit, Verra's Nature Credit, The Wallacea Trust's Biodiversity Credit*) while others only

registered a decrease (e.g. *Organisation for Biodiversity Certificates' Biodiversity Index*). This negative trend suggests a preference for community-level restoration efforts for these two credits.

3.6 Environmental Heterogeneity Restoration Experiment

Ecologists and conservationist highlight the importance of environmental heterogeneity as a proxy for biodiversity, while emphasizing its utility in enhancing biodiversity (39-41). This experiment examines how full environmental homogenisation and consequently a full heterogenization are tracked by the metrics. Unlike the previous experiments, which modelled degradation to a completely uninhabitable environment (e.g. building a container depot in the rainforest), this experiment models a habitable, but entirely uniform environment as the degraded state, subsequently restoring the original heterogeneity. Experiments were conducted using one or two environmental variables. Surprisingly, most metrics did not detect any changes. Among the credits *The Wallacea Trust's Biodiversity Credit* was the only one to reflect the positive impacts of reintroduced environmental heterogeneity. Interestingly, its results were not influenced by the number of environmental variables modelled. In the case of *Verra's Nature Credits* a neutral baseline trend allocation was used, however the use of a negative baseline trend allocation would result in a slight increase. This, however, is only a function of the baseline trend allocation chosen. The Species Threat Abatement and Restoration Metric (STAR) is the only metric that not only reflects the expected positive

change but also accounts for the two levels of complexity in the environment, for both the Threat Abatement and the Restoration variants.

3.7 Discussion

As expected, all biodiversity credits metrics modelled were suitable for reporting on restoration experiments, despite notable discrepancies in the methodologies employed. Most metrics have generated a continuous range of outputs while others opt for thresholding in their methodology and thus result in a categorical output, for example *BioCarbon Registry's Biodiversity Credit* and *The Wallacea Trust's Biodiversity Credit*. This could lead to a loss of sensitivity and mask small changes in the ecosystem. Nevertheless, in the model certain responses, particularly those concerning species conservation, may be overstated due to the relatively small size of the simulated area and the assumption that all species are endemic to this area. Moreover, further study is required to understand the mechanisms governing the simulated metrics' responses to the above-described interventions, as this would allow for the identification of cases where the recorded trends might be artefacts of our methodology.

Crucially, no single credit was universally effective for all six experiments. Specifically, no metric was suitable for measuring both species-specific and environmental heterogeneity restoration. Perhaps the credits were created for specific purposes or within the context of a specific project. Nevertheless, the concept of a universal biodiversity credit, one ideal for all restoration efforts, remains elusive.

Investors are increasingly concerned about the carbon risk in their portfolios (42, 43), and it is anticipated that the same will soon apply to biodiversity risk (44). This, combined with the urgent need for funding for nature restoration, means that there is no time to wait for improved metrics. Accordingly credit-funded nature restoration projects are already underway. As biodiversity credits are part of a nascent, rapidly developing market, credit issuers are incentivised to overstate their credit's capabilities to gain and lock in early market share. Governmental and intergovernmental guidelines are in development but not yet available. Therefore, it is essential for project developers and conservationists to understand which credits are appropriate for which needs, to accurately align funding to which objectives.

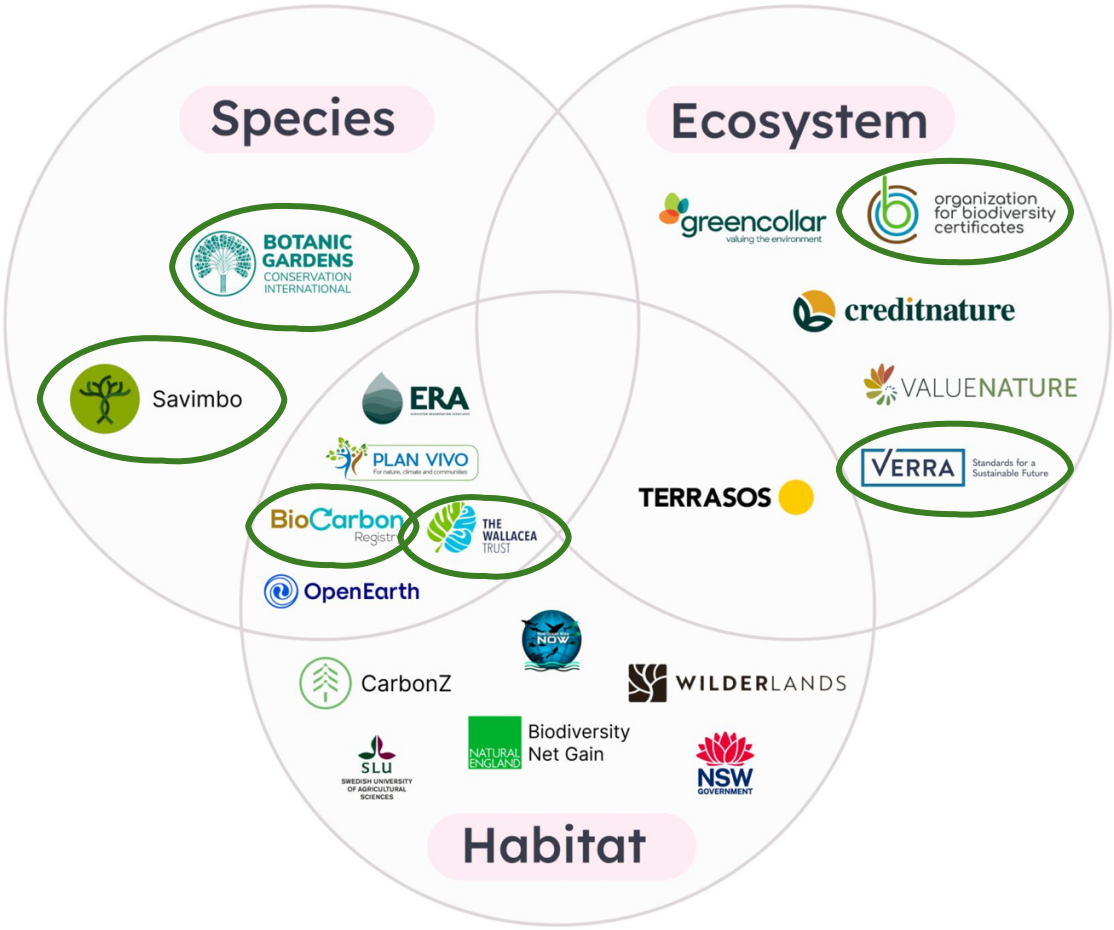
The neoliberalist commodification of nature is a risky endeavour. If successful, it could unlock the urgently required funding required to halt the sixth mass extinction and achieve nature and climate goals. However, if the funding mechanism and ecological impacts are not aligned, funded projects could be ineffective or even have adverse impacts. Furthermore, misalignment could divert funds away from holistic, non-metric-based, nature conservation and restoration projects. Avoiding such mistakes is paramount given the utmost urgency of the required nature restoration, and to avoid reputational damage for the biodiversity credit market.

4. Conclusion

The voluntary biodiversity credit market encompasses a variety of credit issuance methodologies, with some products aiming for a broad assessment of biodiversity, while others focusing on specific aspects of conservation and restoration for instance extinction risk. Our analysis of six distinct voluntary biodiversity credits across a variety of environmental degradation and restoration experiments reveals notable differences in credit responses. This underscores the importance for project developers and conservationists to carefully select the most suitable metric to align with their objectives, thereby preventing discrepancies between the project's objectives and its funding mechanisms. Furthermore, our results that a universal biodiversity credit, akin to carbon credits, seams unfeasible.

5. Figures and Tables

Figure 1.

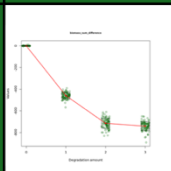
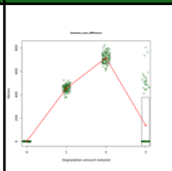
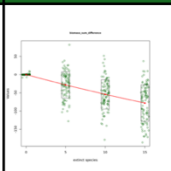
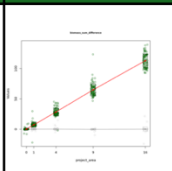
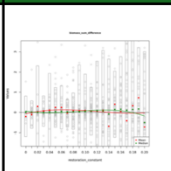
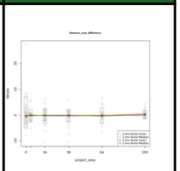
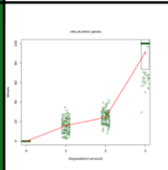
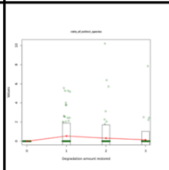
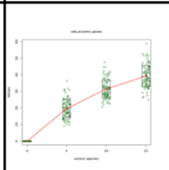
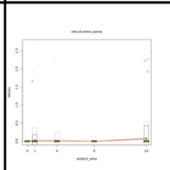
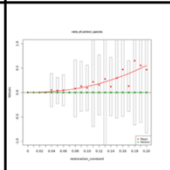
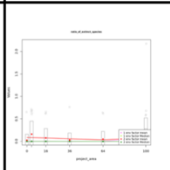
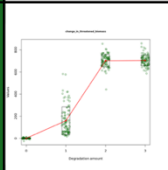
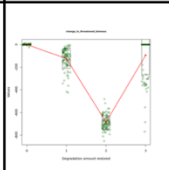
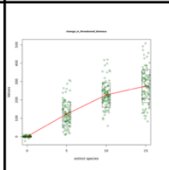
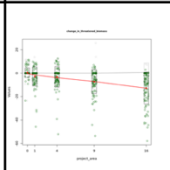
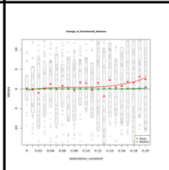
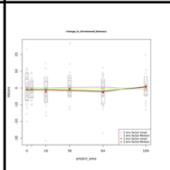
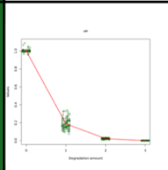
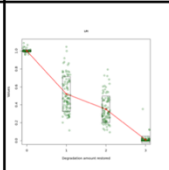
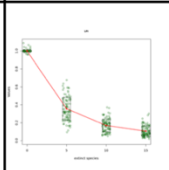
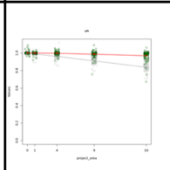
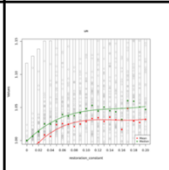
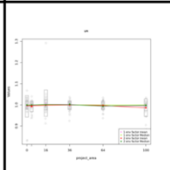
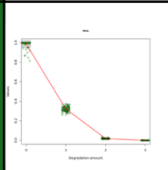
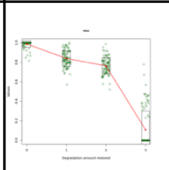
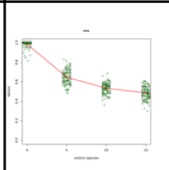
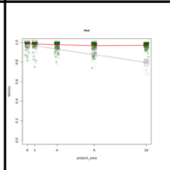
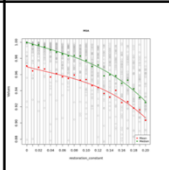
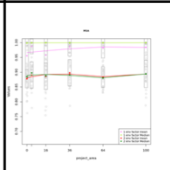
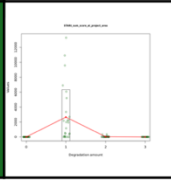
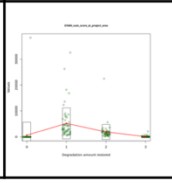
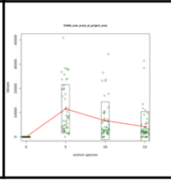
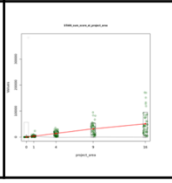
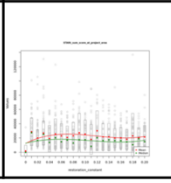
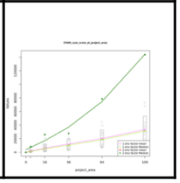


https://sgradeckas.substack.com/p/biodiversity-credit-calculation-overview

Figure 1. shows the variety of voluntary biodiversity credits on the market. The credits are grouped by their level of focus. While some credits are calculated using only a combination of species richness data, others use additional indicators from the habitat and ecosystem levels. Here we examine the six credits highlighted. Figure inspired by on Bloom Labs and Simas Gradeckas.

Table 1.

Table 1displays the results for all six experiments. Each row represents a metric or credit, while each column represents an experiment. Interpretations of the results are in Table 2. All figures in further detail can be found in Appendix 2. Each point signals an independent run with a freshly assembled novel metacommunity. Boxes show the standard deviation, while a red line connects the means. All credits were suitable for measuring simple restoration experiments, however only a few successfully signalled the expected results from species-specific and environmental heterogeneity restoration experiments.

Indicators	Degradation	Restoration	Large extinction event	Increasing Project Area	Species-specific restoration	Restoring environmental heterogeneity
Biomass						
Ratio of Extinct Species						
Change in amount of IUCN threatened						
LPI						
MSA						
STARt						

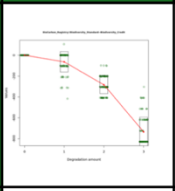
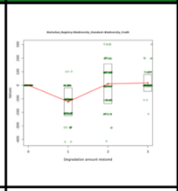
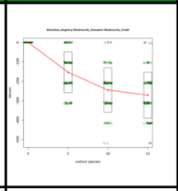
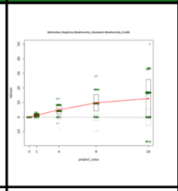
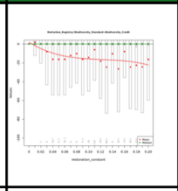
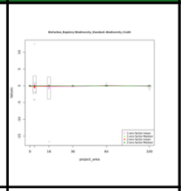
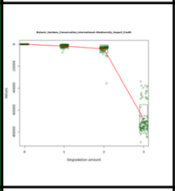
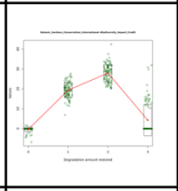
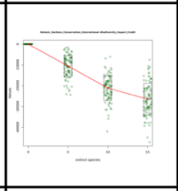
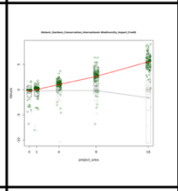
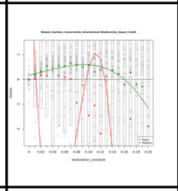
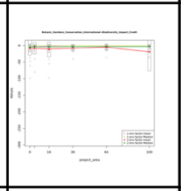
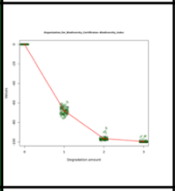
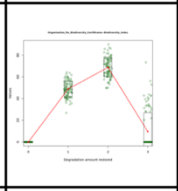
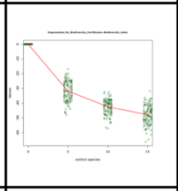
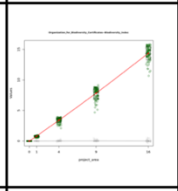
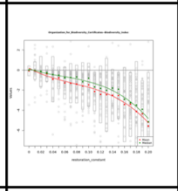
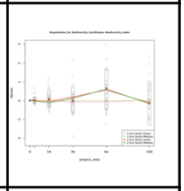
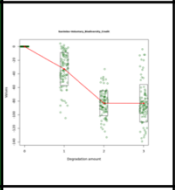
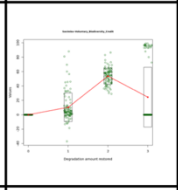
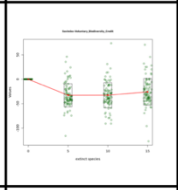
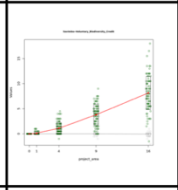
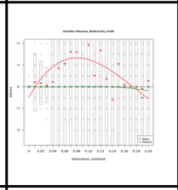
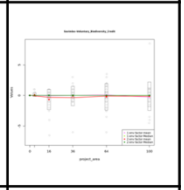
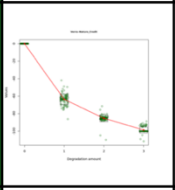
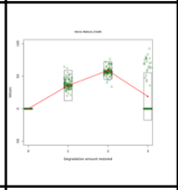
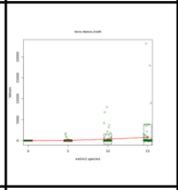
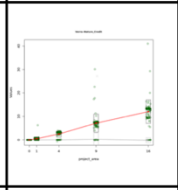
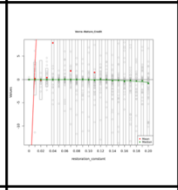
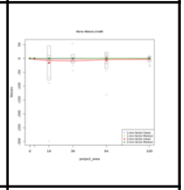
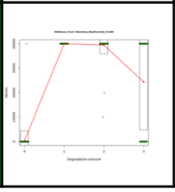
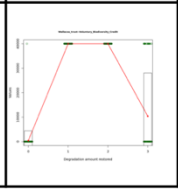
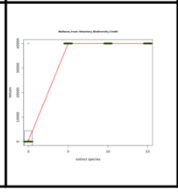
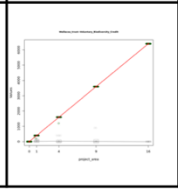
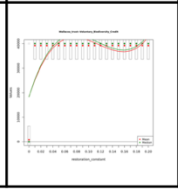
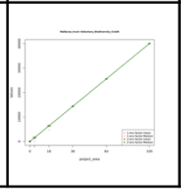
Indicators	Degradation	Restoration	Large extinction event	Increasing Project Area	Species-specific restoration	Restoring environmental heterogeneity
BioCarbon Registry's Biodiversity Credit						
Botanic Gardens International's Biodiversity Impact Credits						
Organisation for Biodiversity Certificates' Biodiversity Index						
Savimbo's Voluntary Biodiversity Credits						
Verra's Net Biodiversity Impacts						
The Wallacea Trust's Biodiversity Credit						

Table 2.

Indicators	Degradation	Restoration	Large extinction event	Increasing Project Area	Species-specific restoration	Restoring environmental heterogeneity
Biomass	Suitable	Suitable	Suitable	Suitable	Not suitable	Not suitable
Ratio of Extinct Species	Suitable	Not suitable	Suitable	Not suitable	Not suitable	Not suitable
Change in amount of IUCN threatened	Suitable	Suitable	Suitable	Suitable	Not suitable	Not suitable
LPI	Suitable	Suitable, relative to the degraded state	Suitable	Suitable	Not suitable	Not suitable
MSA	Suitable	Suitable, relative to the degraded state	Suitable	Suitable	Not suitable	Not suitable
STARt	Suitable	Suitable, relative to the degraded state	Suitable	Suitable	Not suitable	Suitable
BioCarbon Registry's Biodiversity Credit	Suitable	Suitable	Suitable	Suitable	Not suitable	Not suitable
Botanic Gardens International's Biodiversity Impact Credits	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable
Organisation for Biodiversity Certificates' Biodiversity Index	Suitable	Suitable	Suitable	Suitable	Not suitable	Not suitable
Savimbo's Voluntary Biodiversity Credits	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable
Verra's Net Biodiversity Impacts	Suitable	Suitable	Suitable	Suitable	Not suitable	Not suitable
The Wallacea Trust's Biodiversity Credit	Not suitable	Suitable	Not suitable	Suitable	Not suitable	Suitable

Table 2 displays our subjective interpretation of the results shown in Table 1. Each row represents a metric or credit, while each column represents an experiment. All credits were suitable for measuring simple restoration experiments, however only a few successfully signalled the expected results from species-specific and environmental heterogeneity restoration experiments. Some metrics do not have an inherent comparison built in (e.g. LPI, MSA, STARt). In such cases, if the metrics are suitable to quantify environmental restoration when compared to the degraded state, this is indicated.

6. Appendix

6.1 Detailed description of the LVMCM

To accurately simulate the impact of small habitat alterations on landscape-level biodiversity outcomes, a sophisticated spatially explicit model is required. The model incorporates multiple hierarchical elements. The base layer consists of one or two spatially varying environmental variables, representing the real world's diverse environments. These are sampled from a spatially autocorrelated random field, and it allows for various levels of environmental heterogeneity by varying the scale of the autocorrelation. Within this abiotic environment, each simulated species is assigned an intrinsic growth rate by the random allocation of an environmental optimum, that defines the species' preferred abiotic conditions. This allocation introduces the potential for species coexistence into the model, as the preferences of certain species will inevitably overlap. Subsequently, a fixed spatial network is introduced and local sites are connected to adjacent ones via the Gabriel algorithm (45, 46). Dispersal between sites is modelled through these connections. Dispersal length and niche width are kept the same across all species. A network of adverse ecological interaction between the species is constructed by random sampling. These interactions introduce an element of competition and thus limit the number of species that can co-exist at a given site. The behaviour of the species is governed by a system of spatially coupled Lotka-Volterra competition models.

$$\frac{d\mathrm{B}}{dt} = (\mathrm{R} - \mathrm{AB}) \times \mathrm{B} + \mathrm{BD}$$

Here, *t* stands for time, *B* for the biomass matrix, *R* for the spatially explicit growth rate matrix, *A* for the matrix of ecological interactions between the species, and *D* for the connectivity matrix. Iterative invasions are used to construct a representative metacommunity.

6.2 Detailed description of metric implementations

6.2.1 Indicator Species

The LVMCM models complex community dynamics based on a few simple species characteristics: growth rate relative to the environment and species interactions. Consequently, indicator species were chosen according to their relative impact on other species. The three indicator species are:

- The species that has adverse effects on most other species.
- The species that has adverse effects on least other species.
- The species with the largest relative impact on others: This species has the most detrimental effect on others, while being the least affected.

6.2.2 IUCN Red List

The IUCN Red List is a worldwide database of species that categorises species based on their threat of extinction. The main categories are: Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern. To apply these categories to the LVMCM's simulated species, first the proportions of each category was noted according to the 2022-2 IUCN Red List (https://www.iucnredlist.org/statistics). After the initial assembly of the community at each simulation, the simulated species were sorted into the IUCN Red List categories according to these proportions, based on their overall biomass. The highest biomass of each category was recorded as a threshold. After each further timestep simulated, for instance during a degradation or restoration event, the species

were reorganised based these thresholds. Thus, if during a degradation experiment a "Vulnerable" species falls below the "Endangered" threshold, it is recategorized as "Endangered".

6.2.3 IUCN Red List of Ecosystems

Similarly to the IUCN Red List of species, the IUCN Red List of Ecosystems were simulated based on the real-world proportions of each category: Critically Endangered, Endangered, Vulnerable, Near Threatened and of the Least Concern. (https://assessments.iucnrle.org/search statistics tab). Each site is categorised based on its overall Range Size Rarity index after the initial assembly of the metacommunity. The thresholds for each category were noted. After all subsequent simulation events all sites were recategorised according to these thresholds. Therefore, if during a degradation experiment a "Vulnerable" ecosystem falls below the "Endangered" threshold, it is recategorized as "Endangered".

6.2.4 Living Planet Index

The Living Planet Index (LPI) measures the geometric mean of relative change in abundance of all vertebrate species compared to a baseline database from 1970 (33). This was simulated as the geometric mean of the relative abundance of all species in the model. In the LVMCM, the initially assembled healthy community is chosen to be the

baseline state. Any change from this state throughout subsequent experiment is measured, and the geometric mean is calculated.

6.2.5 Mean Species Abundance

The Mean Species Abundance (MSA) aims to describe the ecosystem intactness and quantify ecosystem functioning. The MSA score is calculated by calculating the arithmetic mean for the change in species' abundance between a project site and an undisturbed reference site (32, 35). To calculate the change in species' abundance the abundance at the project site is divided by the abundance at the reference site, while truncating the values at 1. Importantly, invasive species at the project site which are not present at the reference site are not counted. Again, in the LVMCM the initially assembled healthy community is used as the reference state. MSA is computed on a site-by-site basis which are averaged to calculate the MSA for a given area.

6.2.6 Range Size Rarity

Range Size Rarity indicates the relative conservation importance of a given location. For a given species the Range Size Rarity of a given location is the proportion of a species' range contained within the location. By summing the Range Size Rarity values for all species at a given location the overall ecological importance of the location can be measured. Range Size Rarity is implemented on a site-by-site basis in the LVMCM in a

straightforward manner. Presence or absence at a site was determined by the simulation's extinction threshold.

6.2.7 Species Threat Abatement and Restoration Metric

The Species Threat Abatement and Restoration Metric (STAR) measures the impact of changes in an ecological community on species extinction risk (34). (ADD BROOKS 2019) There are two STAR metric values: The STARt score shows the level of threat facing a given species at a given location, while the STARr score shows the effort required to get a given species to the IUCN Red List's Least Concern category. Thus, the sum of STAR scores for all species at a given location represent a proportion of the global opportunity to reduce species' extinction risk through threat abatement and restoration, respectively. While the sum of STAR scores for a given species over all locations represents the global effort needed to get a species to the IUCN Red List's Least Concern category. The START metric is calculates as:

$$T_{t,i} = \sum_{s}^{N} P_{s,i} W_s C_{s,t}$$

Where:

$T_{t,i}$ = Threat Abatement metric

$P_{s,I}$ = the current area of habitat of each species s within location i (expressed as a percentage of the global species' current area of habitat)

W_s = IUCN Red List category weight of species s (Near Threatened = 1; Vulnerable = 2; Endangered = 3; Critically Endangered = 4)

$C_{s,t}$ = The relative contribution of threat t to the extinction risk of species s

N = The total number of species at location i

In the LVMCM, the STARt score is straightforward to implement with the simulated IUCN Red List categories and Range Size Rarity calculations. The Area of Habitat was determined by the species inherent growth rate at a given location. Importantly, as the model does not distinguish between differing threats, C is kept constant at 1. This paper investigates biodiversity metrics and does not account for additional modifications, such as accounting for leakage or a buffer. Therefore, the STARr score is not considered, as the habitat specific restoration multiplier not possible to compute.

6.3 Detailed description of credit implementations

6.3.1 BioCarbon Registry's Biodiversity Credit

Source of Credit Methodology:

https://biocarbonstandard.com/wp-content/uploads/BCR_Methodological-document-NBG.pdf

Summary of methodology:

BioCarbon Registry conceptualise their Biodiversity Credit as a unit of measurement quantifying biodiversity gains at a given area. The number of credits issued is a product of area size and the sum of a wide range of categorised biodiversity metrics. These metrics are the following: Landscape Biodiversity Index, Species richness, Magalef Index of Diversity, Simpson's diversity index, Pielou's Index, Jaccard similarity index, Whittaker Index, Gamma index, High Conservation Values, Number of species in different IUCN Red List categories. For all the above-mentioned metrics BioCarbon Registry's Methodology Paper provides a set of threshold values which assign a numerical value to be used in the sum calculation. After conducting conservation activities and assessments, Biodiversity Credits are issued in response to the positive change in metrics in the project area.

$$BDC_{year} = A_{ci} * (f_{IBP} + f_{NE} + f_{DMG} + f_{D} + f_{J'} + f_{Ij} + f_{\beta} + f_{\gamma} + f_{HCV} + f_{EW} + f_{CR} + f_{EN} + f_{VU} + f_{NT} + f_{LC})$$

Where:

BDC_{year}	=	Biodiversity credits for a given amount of years
A_{ci}	=	The area within the boundaries of the conservation initiative; in hectares
f_{IBP}	=	Landscape Biodiversity Index
f_{NE}	=	Specific richness (number of species)
f_{DMG}	=	Margalef Index of Diversity
f_{D}	=	Dominance index (or Simpson's diversity index)
$f_{J'}$	=	Pileou's Index
f_{Ij}	=	Jaccard similarity index
f_{β}	=	Whittaker index
f_{y}	=	Gamma index
f_{HCV}	=	High Conservation Value
f_{EW}	=	IUCN Red List's Extinct in Wild
f_{CR}	=	IUCN Red List's Critically Endangered
f_{EN}	=	IUCN Red List's Endangered
f_{VU}	=	IUCN Red List's Vulnerable
f_{NT}	=	IUCN Red List's Near Threatened
f_{LC}	=	IUCN Red List's Least Concern

Implementation in the LVMCM:

The majority of the biodiversity metrics required by the BioCarbon Registry Biodiversity Credit are tracked straightforwardly by the LVMCM, these are: Species richness, Magalef Index of Diversity, Simpson's diversity index, Pielou's Index, Whittaker Index, Gamma index, Number of species in different IUCN Red List categories. Further information on how the species are assigned IUCN Red List Categories can be found above. Some of the High Conservation Values (HCVs) must be assessed on a project-by-project basis or are not possible to model in the LVMCM, for instance ecosystem services, community needs or cultural values. Other conditions are almost always guaranteed

within the model, for instance areas of high species diversity. Therefore, the value of HCVs is guaranteed to be between one and three, and therefore the factor allocated is 1.02 and is kept constant, as per the methodology paper.

The model simulates a continuous project area without segmentation, therefore the Jaccard similarity is kept constant at 0.1, and therefore the factor allocated is 1.05.

The Landscape Biodiversity Factor cannot be calculated in the model, as landscape and area configurations are manually provided from outside the model. Therefore, the factor is kept constant at 1.

After these minor modifications the issuable Biodiversity Credits are calculated as the product of area size and the change in the sum of all biodiversity metrics.

6.3.2 Botanic Gardens Conservation International's Biodiversity Impact Credits

Source of Credit Methodology:

http://biodiversitycredits.info/BIC-Methodology-2023.pdf

Summary of methodology:

The Biodiversity Impact Credits (BICs) quantify the changes in the global species extinction risk caused by human interventions to the natural environment. Calculating BICs require the current global population size, the change in the local population affected by the intervention and a regularisation constant protecting against the effect of random extinctions at low population sizes. The BIC for a single species is the change in regional abundance, divided by the sum of the global population and the regularisation constant. Often the regularisation constant is negligibly small compared to the global abundance. BICs for a project area is the sum of all species-specific BICs.

$$BIC = \frac{\Delta N}{N^* + N}$$

Where:

N	=	the current global population size of the species
ΔN	=	the change in the population of the species that resulted from the intervention
N∗	=	regularisation constant as small population sizes a species can go extinct if by chance

Implementation in the LVMCM:

As the LVMCM tracks the exact abundances for all species both in and outside of the project area calculating the BICs is straightforward. The regularisation constant was chosen at 1% of the monoculture carrying capacity of a single site and kept constant.

6.3.3 Organisation for Biodiversity Certificates' Biodiversity Index

Source of Credit Methodology:

https://www.obiocert.com/wp-content/uploads/2022/11/Towards_biodiversity_certificates_proposal_for_a_methodological_framework.pdf

Summary of methodology:

Organisation for Biodiversity Certificate's Biodiversity Index Assessment Method describes a modified mean species abundance (MSA) calculation methodology. The carrying capacity of the project area is estimated by external experts at each assessment, against a predefined reference condition. In the case of the unmodified MSA calculations this reference condition is the 'undisturbed' state of an ecosystem. Assigning such an undisturbed state in practice can be challenging. Moreover, if the plan of restoration is different from the undisturbed state of the ecosystem, the assigned reference values might not even capture the full extent of the restoration efforts. The Organisation for Biodiversity Certificate's Biodiversity Index (BI) circumvents these potential issues by allowing for expert aided free assignment of the BI reference value on a scale of zero to one. Subsequently, the BI is measured at each assessment, and credits can be issued as a product of the additional BI gained compared to the baseline measurement, and project area size.

$$BI = BI_{(ref)} * \frac{1}{N_{reference\ species}} * \sum_{s=1}^{N_{reference\ species}} \min\left(\frac{CC_{observed}(s)}{CC_{reference}(s)}, 1\right)$$

$$Issuable\ Credits = \sum((BI(t) - BI(baseline)) * surface\ area)$$

Where:

BI	=	Biodiversity Index
$BI_{(ref)}$	=	Biodiversity Index of the reference ecosystem
$N_{reference\ species}$	=	Total number of species in the reference ecosystem
$CC_{observed}(s)$	=	Carrying capacity of species s in the assessed ecosystem
$CC_{reference}(s)$	=	Carrying capacity of species s in the reference ecosystem

Implementation in the LVMCM:

For the purposes of the model, carrying capacity has been defined as local biomass over the project area. The BI reference value has been set at one and kept constant, to allow for an unconfounded comparison with alternative credits. Subsequently, the BI values were computed for the degraded and restored states, and the credits issuable are calculated as the product of the difference between the degraded and restored states, and project area size.

6.3.4 *Savimbo's Biodiversity Credit*

Source of Credit Methodology:

https://unit.savimbo.com/unit-of-a-biodiversity-credit

https://isbm.savimbo.com/calculation/integrity-calculations

https://unit.savimbo.com/calculation-of-a-biodiversity-credit

Summary of methodology:

Savimbo's Biodiversity Credit (VBC) is a sum of the difference in integrity over time and area.

$$VBCs = \sum_{a \in A} \sum_{t=1}^{T} (Integrity_{a,t} - Integrity_{a,Baseline})$$

Where:

VBCs	=	Voluntary Biodiversity Credits
a	=	project area
t	=	time passed

Integrity is defined on a spectrum between 0 and 1 where 0 is a completely degraded ecosystem while 1 is a fully intact ecosystem. Integrity is sampled by the presence or absence of indicator species which are chosen by the user to represent the relative health of the ecosystem. If a species is representative a fully intact ecosystem it is assigned 1, however species which survive in more degraded ecosystems would

represent a fractional integrity score. These are summed for each measurement point within the project area; however, the sums cannot exceed 1. Δ Integrity is then calculated by subtracting the baseline Integrity figure from the changed one.

Furthermore, Savimbo track the Value of an ecosystem, which influences the quality of their credits issued. Ecosystem value is determined by public ecosystem indicators. These can be local indicator databases or the IUCN Red List of Ecosystems database.

Implementation in the LVMCM:

In the model, the integrity calculations rely on indicator species. Their selection in the model is described above. To compute a site's integrity score within the project area, the model checks whether any of the three indicator species are present and awards a 0.5 integrity for each indicator species for the site. These are summed and truncated at 1. The site-wise Integrity scores are summed over the project area to calculate the Integrity for a given state in time allowing for the estimation of ΔIntegrity.

For the Ecosystem value term, the IUCN Red List of Ecosystems database is modelled for each assembled community. Further information on how the IUCN Red List of Ecosystems categories are assigned can be found above. The integrity calculations rely on indicator species.

6.3.5 *Verra's Nature Credit*

Source of Credit Methodology:

https://verra.org/wp-content/uploads/2023/09/SD-VISta-Nature-Framework-v0.1-for-Public-Consultation.pdf

Summary of methodology:

The Nature Credit is defined as the biodiversity uplift of one quality hectare equivalent relative to a baseline, due to a project intervention. Quality hectares are a weighted unit of the area size and condition. At the project start, and at each following assessment, the condition of an area is estimated by the arithmetic mean of at least 2 composition and at least 3 structure indicators. All condition indicators are standardised against a reference site. Subsequently, the net biodiversity impact is calculated by comparing the condition-adjusted area figures at the project start with those at the current time, adjusting for leakage and the area's global significance. After adjusting by an area-specific buffer value, the Nature Credits are ready to issue.

$$C = \frac{\left(\frac{St_1 + St_2 + \cdots St_n}{n}\right) + \left(\frac{Cm_1 + Cm_2 + \cdots Cm_n}{l}\right)}{2}$$

Where:

C	=	Condition indicator at a given time
St	=	Standardised structure indicators at the given time
Cm	=	Standardised composition indicators the given time

n	=	Number of structure indicators
l	=	Number of composition indicators

$$NBI = E_t C_t - E_0 C_0 (1 + t * B) - L$$

$$Buffer = E_t C_t - E_0 C_0 (1 + t * B) * 0.2$$

$$NC = NBI - Buffer$$

Where:

NC	=	Nature Credit
NBI	=	Net Biodiversity Impacts in quality hectare
E_t	=	Extent in hectares at project monitoring date
C_t	=	Condition at project monitoring date
E_0	=	Extent in hectares at project start
C_0	=	Condition at project start
t	=	Number of years from project start
B	=	Project crediting baseline
L	=	Leakage

Implementation in the LVMCM:

Calculation of the issuable Nature Credits for a given project can vary based on which metrics are selected as indicators. As the LVMCM grants the opportunity of observing the same site in different conditions, the reference site is defined as the project site in its undisturbed state immediately after assembly. The time variable has been kept constant, to allow for an unconfounded comparison with alternative credits. The following metrics were chosen as the three structure indicators: Abundance of the most abundant species,

total biomass, and species richness. As the two composition indicators, indicator species abundances were used. These were assigned by sampling the species with the smallest negative impact on other species, and the species with the largest negative impact on other species. Further information on how the indicator species were chosen can be found above. The project crediting baseline (B) was kept constant at 0, to allow for an unconfounded comparison with alternative credits. This paper investigates biodiversity metrics and does not account for additional modifications to compute the final credits, such as accounting for leakage or a buffer. Therefore, NBI value was used in comparisons with other credits.

6.3.6 *The Wallacea Trust's Biodiversity Credit*

Source of credit methodology:

https://wallaceatrust.org/wp-content/uploads/2022/12/Biodiversity-credit-methodology-V2.1.pdf

Summary of methodology:

Wallacea trust define their Biodiversity Credit metric as a measured 1% uplift or avoided loss in biodiversity per hectare. Biodiversity values are measured as a median of a basket of minimum five metrics, one of which is an obligatory structural metric, while the rest are a score calculated from the relative abundance and conservation value of larger assemblages of species. Each metric is simplified by thresholding into a five-point scale based on conformity with a pre-defined and analogous reference site. Subsequently, the biodiversity uplift is estimated based on the change in biodiversity values (Vm), and after accounting for a buffer and loss, the claimable Biodiversity Credits are issued.

$$V_m = \left[\sum_{s=1}^{S} A_s * CV_s\right]$$

Where:

Vm	=	Overall biodiversity value for a sampling category
As	=	Relative abundance scores of each assigned on a 5-point scale
CVs	=	Conservation Value scores of each species is assigned on a 5-point scale

$$B_{u(t)} = 100 * \frac{V_{m(ps,t)} - V_{m(ps,t0)}}{V_{m(ps,t0)}}$$

Where:

$Bu(t)$	=	Biodiversity uplift value for a given metric at a verification event
Vm	=	Overall biodiversity value for a sampling category

$$BDC_{(uplift)} = b * \left[B_u * \left(A_{p(restored)} - l\right)\right]$$

Where:

$BDC(uplift)$	=	Number of claimable biodiversity credits issued for an uplift project
b	=	Adjustment to account for the buffer retained by the registry issuing the credits for their insurance pool (this adjustment value is usually set at 0.8)
Bu	=	Median biodiversity uplift value across the different metrics after any adjustments have been made for uncertainty
$Ap(restored)$	=	Effective area in hectares within the Project Site restored over the Project
l	=	Number of hectares lost to leakage issues

Implementation in the LVMCM:

For the purposes of this research the focus is on biodiversity increase and not avoided loss, therefore we focus on Wallacea Trust's Biodiversity Credit's uplift calculations. As the LVMCM grants the opportunity of observing the same site in different conditions, the reference site is defined as the project site, in its undisturbed state immediately after

assembly. The obligatory structural metric is interpreted as the overall biomass within the project area at a time. Relative abundance of species is tracked throughout the experiments, while for the conservation value the IUCN Red List categories are used, in line with Wallacea methodology. Further information on how the species are assigned IUCN Red List Categories can be found in the Appendix. Unfortunately, the LVMCM model in its current form only recreates intra-guild competition, therefore the requirement for measuring 'larger assemblages of species' is satisfied by grouping species based on their interspecies interaction characteristics. The chosen four groups of species are as follows: the group of species with the smallest negative impact on other species; the group of species with the largest negative impact on other species, the group of species with the largest overall impact on other species, and the group of species which have the largest biomass in the reference condition. These metrics are subsequently categorised on the five-point scale against the reference condition, and after conducting the calculations for both the degraded and restored states an evaluation of Biodiversity Credits issuable is estimated. This paper investigates biodiversity metrics and does not account for additional modifications to compute the final credits, such as accounting for leakage or a buffer. Therefore, the *b* value was kept constant at 1.

7. References

1. Agreement P, editor Paris agreement. report of the conference of the parties to the United Nations framework convention on climate change (21st session, 2015: Paris) Retrived December; 2015: HeinOnline.
2. Hisano M, Searle EB, Chen HYH. Biodiversity as a solution to mitigate climate change impacts on the functioning of forest ecosystems. Biological Reviews. 2018;93(1):439-56.
3. Rizzi C. Nature as a defense from disasters: Natural capital and municipal bond yields. Available at SSRN 4038371. 2022.
4. Thompson I, Mackey B, McNulty S, Mosseler A, editors. Forest resilience, biodiversity, and climate change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems Secretariat of the Convention on Biological Diversity, Montreal Technical Series; 2009.
5. Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM, Palmer TM. Accelerated modern human–induced species losses: Entering the sixth mass extinction. Science Advances. 2015;1(5):e1400253.
6. Díaz S, Hector A, Wardle DA. Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Current Opinion in Environmental Sustainability. 2009;1(1):55-60.
7. Diversity SotCoB. Review of the Literature on the Links Between Biodiversity and Climate Change: Impacts, adaptation, and mitigation. 2009.
8. Gracia A, Rangel-Buitrago N, Oakley JA, Williams AT. Use of ecosystems in coastal erosion management. Ocean & Coastal Management. 2018;156:277-89.
9. Yang Y, Tilman D, Furey G, Lehman C. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nature Communications. 2019;10(1):718.
10. Jantz SM, Barker B, Brooks TM, Chini LP, Huang Q, Moore RM, et al. Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. Conservation Biology. 2015;29(4):1122-31.
11. Pörtner HO, Roberts DC, Adams H, Adler C, Aldunce P, Ali E, et al. Climate change 2022: Impacts, adaptation and vulnerability. IPCC; 2022.
12. Warren R, VanDerWal J, Price J, Welbergen JA, Atkinson I, Ramirez-Villegas J, et al. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. Nature Climate Change. 2013;3(7):678-82.
13. Contestabile M. Joined-up action for biodiversity. Nature Sustainability. 2021;4(8):660-1.
14. Parties Co. Decision Adopted by the Conference of the Parties to the Convention on

Biological Diversity. Kunming-Montreal Global Biodiversity Framework. 2022.

15. Deutz A, Heal GM, Niu R, Swanson E, Townshend T, Zhu L, et al. Financing Nature: Closing the global biodiversity financing gap. The Paulson Institute, The Nature Conservancy, and the Cornell Atkinson Center for Sustainability. 2020:256.

16. Xu H, Cao Y, Yu D, Cao M, He Y, Gill M, et al. Ensuring effective implementation of the post-2020 global biodiversity targets. Nature Ecology & Evolution. 2021;5(4):411-8.

17. Seidl A, Mulungu K, Arlaud M, van den Heuvel O, Riva M. Finance for nature: A global estimate of public biodiversity investments. Ecosystem Services. 2020;46:101216.

18. Dempsey J, Suarez DC. Arrested development? The promises and paradoxes of “selling nature to save it”. Annals of the American Association of Geographers. 2016;106(3):653-71.

19. Dasgupta P. The economics of biodiversity: the Dasgupta review: Hm Treasury; 2021.

20. IPBES W. Intergovernmental science-policy platform on biodiversity and ecosystem services. Summary for Policy Makers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services IPBES Secretariat, Bonn, Germany. 2019.

21. Dempsey J, Irvine-Broque A, Bigger P, Christiansen J, Muchhala B, Nelson S, et al. Biodiversity targets will not be met without debt and tax justice. Nature Ecology & Evolution. 2022;6(3):237-9.

22. McElwee P, Turnout E, Chiroleu-Assouline M, Clapp J, Isenhour C, Jackson T, et al. Ensuring a post-COVID economic agenda tackles global biodiversity loss. One Earth. 2020;3(4):448-61.

23. Otero I, Farrell KN, Pueyo S, Kallis G, Kehoe L, Haberl H, et al. Biodiversity policy beyond economic growth. Conservation Letters. 2020;13(4):e12713.

24. Arlaud M, Cumming T, Dickie I, Flores M, van den Heuvel O, Meyers D, et al. The Biodiversity Finance Initiative: An Approach to Identify and Implement Biodiversity-Centered Finance Solutions for Sustainable Development. In: Leal Filho W, Pociovălișteanu DM, Borges de Brito PR, Borges de Lima I, editors. Towards a Sustainable Bioeconomy: Principles, Challenges and Perspectives. Cham: Springer International Publishing; 2018. p. 77-98.

25. Karolyi GA, Tobin-de la Puente J. Biodiversity finance: A call for research into financing nature. Financial Management. 2023;52(2):231-51.

26. O’Sullivan JD, Knell RJ, Rossberg AG. Metacommunity-scale biodiversity regulation and the self-organised emergence of macroecological patterns. Ecology Letters. 2019;22(9):1428-38.

27. O’Sullivan JD, Terry JCD, Rossberg AG. Intrinsic ecological dynamics drive biodiversity turnover in model metacommunities. Nature Communications. 2021;12(1):3627.

28. O'Sullivan JD, Terry JCD, Wilson R, Rossberg AG. Community composition exceeds area as a predictor of long-term conservation value. PLOS Computational Biology. 2023;19(1):e1010804.

29. Keith DA, Rodríguez JP, Rodríguez-Clark KM, Nicholson E, Aapala K, Alonso A, et al. Scientific Foundations for an IUCN Red List of Ecosystems. PLOS ONE. 2013;8(5):e62111.

30. Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. Biodiversity hotspots for conservation priorities. Nature. 2000;403(6772):853-8.

31. Rodrigues ASL, Pilgrim JD, Lamoreux JF, Hoffmann M, Brooks TM. The value of the IUCN Red List for conservation. Trends in Ecology & Evolution. 2006;21(2):71-6.

32. Alkemade R, van Oorschot M, Miles L, Nellemann C, Bakkenes M, ten Brink B. GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. Ecosystems. 2009;12(3):374-90.

33. Collen B, Loh J, Whitmee S, McRae L, Amin R, Baillie JEM. Monitoring Change in Vertebrate Abundance: the Living Planet Index. Conservation Biology. 2009;23(2):317-27.

34. Mair L, Bennun LA, Brooks TM, Butchart SHM, Bolam FC, Burgess ND, et al. A metric for spatially explicit contributions to science-based species targets. Nature Ecology & Evolution. 2021;5(6):836-44.

35. Schipper AM, Hilbers JP, Meijer JR, Antão LH, Benítez-López A, de Jonge MMJ, et al. Projecting terrestrial biodiversity intactness with GLOBIO 4. Global Change Biology. 2020;26(2):760-71.

36. B. Lindenmayer D, Fischer J, Felton A, Montague-Drake R, D. Manning A, Simberloff D, et al. The complementarity of single-species and ecosystem-oriented research in conservation research. Oikos. 2007;116(7):1220-6.

37. Runge CA, Withey JC, Naugle DE, Fargione JE, Helmstedt KJ, Larsen AE, et al. Single species conservation as an umbrella for management of landscape threats. PLoS One. 2019;14(1):e0209619.

38. Simberloff D. Flagships, umbrellas, and keystones: Is single-species management passé in the landscape era? Biological Conservation. 1998;83(3):247-57.

39. Larkin DJ, Bruland GL, Zedler JB. Heterogeneity Theory and Ecological Restoration. In: Palmer MA, Zedler JB, Falk DA, editors. Foundations of Restoration Ecology. Washington, DC: Island Press/Center for Resource Economics; 2016. p. 271-300.

40. Rocchini D, Balkenhol N, Carter GA, Foody GM, Gillespie TW, He KS, et al. Remotely sensed spectral heterogeneity as a proxy of species diversity: Recent advances and open challenges. Ecological Informatics. 2010;5(5):318-29.

41. Stein A, Gerstner K, Kreft H. Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales. Ecology Letters. 2014;17(7):866-80.

42. Bolton P, Kacperczyk M. Do investors care about carbon risk? Journal of Financial Economics. 2021;142(2):517-49.

43. Naaraayanan SL, Sachdeva K, Sharma V. The real effects of environmental activist investing. European Corporate Governance Institute–Finance Working Paper. 2021(743).

44. Akey P, Appel I. Environmental externalities of activism. Available at SSRN 3508808. 2019.

45. Gabriel KR, Sokal RR. A New Statistical Approach to Geographic Variation Analysis. Systematic Biology. 1969;18(3):259-78.

46. Matula DW, Sokal RR. Properties of Gabriel Graphs Relevant to Geographic Variation Research and the Clustering of Points in the Plane. Geographical Analysis. 1980;12(3):205-22.