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A Review of Condition Metrics Used in Biodiversity Offsetting

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Abstract

Biodiversity offsets are commonly used to compensate for environmental impacts, but their effectiveness is often questioned. Estimations of expected losses and gains often rely on what we called condition metrics, which measure a site's quality or condition using certain ecological attributes. Condition metrics are central to most offset policies, but their attributes and calculations vary substantially. We reviewed the academic literature to draw a profile of existing condition metrics used in the offsetting context. We found 17 metrics that differed in how they included attributes from the three "dimensions of equivalence": biodiversity (present in 15 metrics), landscape (in 10 metrics) and ecosystem services (in 5 metrics). Most metrics included many ecological attributes and required fieldwork and GIS data to be calculated, but few used modeling and expert opinion. Generally, metrics aggregated the attributes into a single final value and were created in Global North countries. To favor more transparent and ecologically equivalent offset trades worldwide, we suggest condition metrics should include the three dimensions of equivalence in a disaggregated way, i.e. measurements done separately and analyzed in parallel. The use of modeling, expert opinion and GIS may facilitate the inclusion of the dimensions and reduce the need for intensive (and expensive) fieldwork. Testing synergies and trade-offs among attributes could indicate if metrics can be simplified without losing information. Finally, development of fit-for-purpose condition metrics is especially important in Global South countries, where few such metrics exist.

Keywords Biodiversity conservation · Offset metrics · Ecological compensation · Public policy · Ecological equivalence

Introduction

Biodiversity offsets have been increasingly adopted by governments and the private sector (GIBOP 2019; Bull and Strange 2018; Gonçalves et al. 2015), and their popularity appears unlikely to change (Maron et al. 2016). They are a strict type of environmental compensation for biodiversity losses (BBOP 2012a) that aims to achieve no net loss (NNL) of biodiversity, seeking ecological equivalence between losses and gains in impacted and offset areas, respectively (BBOP 2012b). The implementation of offsets has been increasing including in Global South countries, but still most offsets are in the Global North (Bull and Strange 2018). The effectiveness of offsets has often been questioned and their implementation faces important challenges (Robinson 2009; Walker et al. 2009; Bull et al. 2013; Apostolopoulou and Adams 2017; zu Ermgassen et al. 2019), particularly with respect to achieving their goals (e.g. NNL) and to the transparency in their implementation and mensuration methods (Maron et al. 2016).

Part of this mistrust comes from the premise that is frequently possible to achieve ecological equivalence between impacted areas and compensation areas (Gonçalves et al. 2015). Ecological equivalence means that both the type and the amount of gains are the same as the losses (BBOP 2012a). *Equivalence of type* is usually achieved through a combination of the *currency* – the kinds of ecological elements that will be traded in an offset process (e.g. species, landscape or ecosystem types) and how these kinds will be numerically compared – and the *rules* that regulate the trading (e.g. trades must happen within the same vegetation type and within the same sub-region). Ecological elements

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that are not in the currency calculation may be included in a rule. The rules of an offset policy set the parameters of what can be considered ecologically equivalent and therefore traded, and may vary from place to place and across time.

Equivalence of amount is the quantification of biodiversity losses and gains in offset processes and the calculations needed to perform trades, based on the estimated losses and gains, time lags and other factors (BBOP 2012a). Calculation approaches that account for equivalence of amount are sometimes called "loss-gain metrics". They require, as a first step, the identification of a currency for use in the calculation. This currency often comprises one or more measures of the quality or condition of a vegetation or habitat type. With this 'ecological condition' value, loss-gain metrics can calculate how much will be lost in the impact site and how many units of that currency will be necessary in the offset site to adequately offset the impact (Gibbons et al. 2016).

Here, we focus on what we call condition metrics – those used to generate a currency to calculate losses and gains. Condition metrics (CM) quantify the condition or quality of a site based on one or more ecological elements and are commonly used when the target of an offset trade is an ecosystem or vegetation type. Many CM have been developed, studied and applied (McKenney and Kiesecker 2010; Quétier and Lavorel 2011; Bezombes et al. 2017; Gamarra et al. 2018). Such metrics can require large amounts of data in order to be calculated (e.g. Pöll et al. 2016; Drobnik et al. 2020) and can be highly complex. On the other hand, simpler and easy-to-understand metrics may be too simplistic to reflect complex entities (Quétier and Lavorel 2011). Metrics can be narrowly applicable to particular biodiversity targets, which diminishes their breadth of application, but improves like-for-like outcomes (Hanford et al. 2017; Quétier and Lavorel 2011). The data in CM may be aggregated, resulting in a single value representing all the ecological elements targeted. This means that substitutions among these elements can occur, often in an unclear way (Gibbons and Lindenmayer 2007; Maseyk et al. 2016; Hanford et al. 2017). These implicit substitutions may bring undesirable outcomes to biodiversity (Maron et al. 2016), such as exchanging an element of higher conservation value by another of lower value (Walker et al. 2009; Bull et al. 2015), or falling to reflect important but more subtle differences between sites (Hanford et al. 2017). Moreover, CM developed for a certain region may not adapt well to other regions, at least not without careful adjustments (Bull et al. 2014b). Thus, it seems important to understand the regional context in which each metric was developed before applying it.

According to BBOP (2012b), ecological equivalence in offsetting schemes refers to 'like-for-like' trades of losses and gains - i.e. the elements traded are equivalent in both their type and their amount. Achieving a like-for-like trade ideally requires consideration of biological diversity and functionality, ecological condition, landscape context and ecosystem services (ES) (BBOP 2012b). These general aspects are important to the concept of ecological equivalence and thus should be included in offset trades. A transparent measurement of sites' conditions for these aspects should enhance the ecological equivalence in trades. Here, we grouped these general aspects into three categories: biodiversity, landscape, and ecosystem services, which we called "dimensions of equivalence". Species richness measurements are an example of an attribute of the biodiversity dimension; the habitat amount in the landscape is an example of a landscape dimension attribute; the pest control service of sites is an example of an ecosystem services dimension attribute.

Biodiversity is clearly important to include in offset exchanges, but landscape and ES inclusion are also relevant. The relationships among impact and offset sites and their surrounding landscape matter (Bruggeman et al. 2005) and offsets typically occur in contexts of human-driven degradation and landscape fragmentation, factors that affect both biodiversity processes and ecosystem services (Mitchell et al. 2015; Sonter et al. 2020). Also, understanding the links between social and ecological factors helps to ensure offset implementation and effectiveness (Habib et al. 2013). However, many offset metrics have been criticized for not capturing landscape and social-environmental aspects (Jacob et al. 2016; Apostolopoulou and Adams 2017; Bidaud et al. 2017) and it has been recommended that including biodiversity features alone is not adequate (Bull et al. 2013).

Given the importance and the challenges related to the use of condition metrics (CMs) in offsetting, our goal in this work was to understand how they function, according to their original conceptualization, and their potential contribution to reach ecological equivalence in trades. Therefore, we conducted a review of the peer-reviewed literature to investigate (1) how they are calculated, (2) what dimensions of equivalence (i.e. biodiversity, landscape and ecosystem services) CM measure, (3) how data demanding they are, (4) how data are aggregated, and (5) under what regional and ecological context they were developed. We did not focus on how they are applied via different policies, nor on the policies' rules. Based on our findings, we profiled existing CM, examined their limitations relative to their practical application and to contributing to ecological equivalence achievement, and suggested how they can become more efficient and transparently implemented in offsetting.

Methods

An increasing number of countries are using offset schemes (GIBOP 2019), but often the metrics they use are

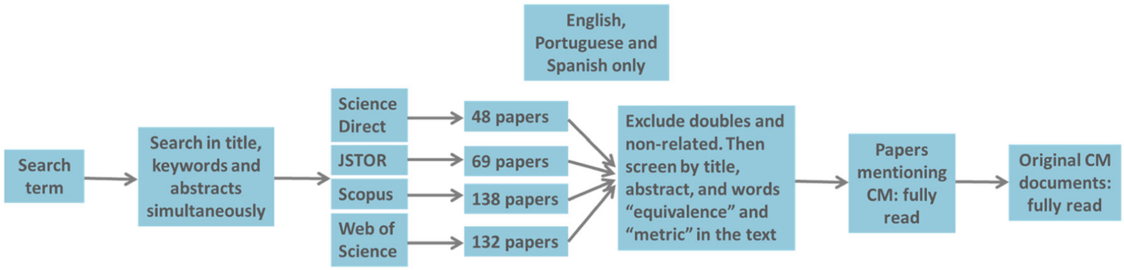

Fig. 1 Step-by-step scheme of our online literature search

documented only in the gray literature. Accessing a range of gray literature in several languages is challenging (Theis et al. 2020), especially when the goal is to make a detailed review. The Global Inventory of Biodiversity Offsets Policy (GIBOP 2019) provides summarized information on policies from around the world, including translated non-English versions when possible. However, our search was restricted to the academic peer-reviewed literature, with the aim of capturing the more widely known condition metrics used in offsets that have been through peer-review processes, which are therefore likely to be more sophisticated and robust. If a condition metric was cited in the papers we reviewed, but not described in them, it was included as well. To understand these metrics in detail, we searched for the original documents that described them, whether they were academic or gray-literature documents.

On 21st May 2018, we conducted a search on online literature databases (Science Direct, JSTOR, Scopus, Web of Science) in English, Spanish, and Portuguese, and we updated the search on 13th November 2020. We used a compound search term that combined the general ideas of biodiversity offset, metric, and ecological equivalence *("ecolog* offset*" OR "biological offset*" OR "environmental offset*" OR "biodiversity offset*") AND (metric* OR measure* OR index OR indices OR calculation* OR variabl*)*. We screened all papers to select those that discussed offset condition metrics (Fig. 1), defined as approaches to calculating a sites ecological quality or condition which are used to compare the condition of losses and gains of two or more sites in an offset scheme.

To answer the five questions we proposed, we collected a large set of information on ecological and calculation characteristics of each CM, summarized in Table 1. We also created a specific scheme, shown in Fig. 2 and further explained below, to extract information on how each CM included ecological attributes related to each of the three dimensions of equivalence. By "ecological attributes" we mean all the ecological variables that are directly measured in each metric (Table 1).

Since each dimension of equivalence is broad, we subdivided each into a number of components (Fig. 2), and each component is measured by one or more ecological attributes. After reviewing the original instructions and the ecological attributes measured in each CM formula, we searched for the components they belonged to, so we could understand which dimensions of equivalence were being incorporated by each metric. We considered numerical and categorical attributes for all components. *Biodiversity dimension* was subdivided into species features (e.g. species richness and composition) and structure, i.e. all the measurements made to understand habitat and population structures. *Landscape dimension* was subdivided into composition and configuration, i.e. the amount of landscape units and how these units are arranged in space, respectively (Fahrig 2005). *Ecosystem services dimension* represents the inclusion of the social-environmental aspects involving ecological equivalence, as they are human benefits derived from ecosystems processes (TEEB 2010), and were subdivided into provision, regulating and cultural services.

The similarity indices of Sorenson and Morisita-Horn used, for example, by Curran et al. (2014) to measure restoration success in offset context, comparing the species similarity of secondary-growth and old-growth communities, were not included in our CM list. This is because these metrics compare the similarity of two sites, whereas our review focuses on metrics that are used to measure condition at each site separately. Normally, the offset exchange has to be within a category or class deemed to be similar enough a priori, then the amounts of gain and loss are compared – using condition metrics – and the similarity comparison itself is not used.

Results

After excluding duplicates and papers non-related to offsets, our search returned a total of 170 unique papers. We screened these and found 31 papers that either described or mentioned one or more condition metrics (CMs), so these 31 papers were fully read. In these papers, we identified a total of 17 unique CMs. However, they were not all described in the 31 papers: six CMs were described in six of these papers, but two were described in two academic papers that were not captured by our search, and nine CMs were described either in some kind

Table 1 Items used to extract information from the condition metrics (CMs) reviewed and the questions to which each item is related

Item	Definition and categories	Answers to which question (Q)
Ecological attributes	The ecological variables specifically measured and included in the CM formula. These attributes were used to assess which dimensions of equivalence were included in each metric (see text below).	Q1, Q2, Q3
Mathematical formula	General mathematical expression of each metric according to the ecological attributes it measures and the mathematical relationships among them.	Q1, Q4
Original instructions	Instructions found in CMs original papers that defined how the metric should be calculated and/or how its results should be compared (their implementation may have deviated from the original intent, but we focused on the original instructions). These instructions were used to assess which dimensions of equivalence were included in each metric (see text below).	Q1, Q2, Q3, Q4
Institution and country that developed the CM	The type of institution (government, company, academy or NGO) responsible for the development of the CM and its original country.	Q5
Benchmark	A reference state reflecting good condition for a given ecological attribute with which the value of the attribute at the site in question can be compared to (BBOP 2012b). We evaluated whether the metric used benchmarks and what reference state they consider.	Q1, Q3
Metric aggregation level	Whether metrics accounted for one ecological attribute type in a simple formula (hence called single-attribute metrics), aggregated attributes (many attributes in one complex formula, resulting in a single value), or disaggregated measures (many attributes in separate formulas, whose results are analyzed in parallel) (adapted from Maseyk et al. 2016).	Q1, Q4
Method and data requirements	The methodological procedure and type of data the metric demand to be calculated: fieldwork, database (consolidated on field and/or laboratory work), GIS (mapping data), expert opinion (opinion of specialists on a given subject), modeling (analysis to generalize different types of data).	Q1, Q3

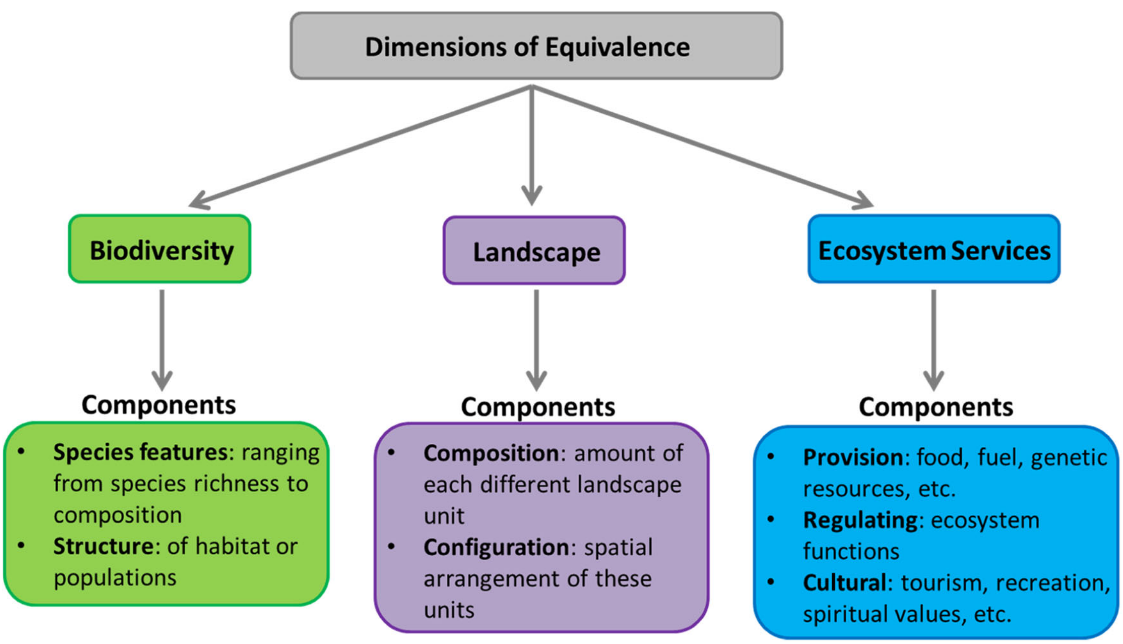

Fig. 2 Dimensions of equivalence considered in this review and their respective components

of policy or technical report (gray-literature documents). Thus, we fully read nine gray-literature documents and eight (six from our search and two additional ones) academic papers describing CMs, a total of 17 documents (one per CM). In the Supplementary Material we provided information about the 31 papers included in this review (Supplementary Table S1) and the raw data collected from the condition metrics (Supplementary Table S2).

The majority of the CMs reviewed were created specifically to the offsetting context, but five metrics were not (HEP, FWCI, SEV, CRAM, SQUID; see below). The CMs general characteristics are described in Table 2.

Nearly all metrics demand data from GIS and fieldwork and/or consolidated databases (Fig. 3). A few also demand data from modeling and expert opinion (i.e. data estimated by experts each time the metric is applied). GIS data are used to map study areas, define vegetation types and calculate area and landscape metrics. Data from fieldwork or a well-established database are usually the basis for site-level CM calculation of most ecological attributes considered in each metric, as remotely-sensed data are often insufficient to collect the necessary information at the fine resolution required. All CMs incorporated at least one component from the biodiversity dimension of equivalence (Fig. 4), except for LCI and SQUID, which incorporated solely landscape and ecosystem service components, respectively. The landscape dimension showed an intermediate level of inclusion (10 CMs) and the ecosystem services dimension was included in only five CMs.

Most CMs have more than seven ecological attributes (Fig. 5), with a mean of 8.8 attributes per metric. Three are single-attribute metrics (total area of habitat in the buffer, number of endemic/threatened species and species dispersal probability), two are measured in a disaggregated framework (LRR and DMRH) and the remaining are aggregated (12). This means that, for most metrics, the numerous attributes that enter the metrics are summarized in a single-value result. The majority of metrics were developed by academia, government or a collaboration of both, but some were developed by companies and NGOs as well (Fig. 6). Most CMs were created in countries of the Global North: United States (3), England (3), Switzerland (3), Australia (3), Wales (1), Austria (1), France (1) and New Zealand (1); one CM was created in Colombia (LCI). Benchmarks are present in 11 metrics, either related to the metric's final score or to the attributes in the metric's formula. Most benchmarks (8) represented the quality of an undisturbed ecosystem, one represented the quality of a pre-impact habitat (ECF) and two were about the optimum carrying capacity for a given species (HEP and SHEP). The characteristics of the CMs reviewed related to their method requirements and dimensions of equivalence incorporated are in Supplementary Table S3.

Discussion

We found 17 condition metrics (CMs) in the peer-reviewed literature that are used to create currencies for comparing losses and gains in offsetting. In general, these CMs incorporated biodiversity attributes, but often lacked attributes from the landscape and ecosystem services dimensions. Some of the CMs were not designed specifically for offsetting, or were designed to a specific offsetting situation, thus they may be appropriate to their primary goals. However, when applied to general offset schemes, the lack of the dimensions of equivalence may reduce ecological equivalence in trades (BBOP 2012b). Many CMs depend on a large number of ecological attributes, which are highly aggregated in almost all CMs formulas, meaning attributes can substitute for one another. Finally, most CMs reviewed were created in Global North countries, usually for particular environmental contexts (e.g. a type of vegetation or an aquatic ecosystem).

The Dimensions of Equivalence

The predominance of the biodiversity dimension of equivalence in condition metrics was expected, since it has been included in offsetting for many years (Bull et al. 2013; Carreras Gamarra et al. 2018; Gonçalves et al. 2015). Including biodiversity in offsetting is an advance compared to a currency of area alone – the area of the offset should be at least the same size as the area impacted (King and Price 2004). Despite their common inclusion in CMs, biodiversity attributes tended to be limited to species richness and habitat measures. Biodiversity is a general term that includes multitudes of characteristics, so measuring it more holistically is always a challenge (Walker et al. 2009). To address such challenge, the use of proxies that represent other biodiversity elements is frequent and may be preferable (Kiesecker et al. 2009), yet choosing such elements is not trivial and their relationships with the proxies are not always clear or strong (Kiesecker et al. 2009; Marshall et al. 2020a; Marshall et al. 2020b). Broader habitat-pattern metrics often do not reflect the ecological processes important to species persistence (Marshall et al. 2020a), which is the ultimate goal of conservation. Among the CMs, measures of vegetation structure and/or composition were the most common, which may not be sufficiently related to species persistence in offset sites (Marshall et al. 2020b). A series of species-specific metrics would be ideal, but they are also data-demanding (Marshall et al. 2020a). We suggest below ways for diminishing the amount of data demanded by a CM.

The landscape dimension was incorporated in more than half of the CMs (10), an intermediate an positive level of inclusion, considering the frequent criticism in the literature about its absence in offsetting (Bruggeman et al. 2005; Gardner et al. 2013; Underwood 2011; Reid et al. 2015). Its inclusion in CMs seems heterogeneous though: in some cases, it has happened for a longer time (e.g. Habitat Hectares in Australia - Parkes et al. 2003), and in others, it is more recent (e.g. qualitative landscape inclusion in offsets

Table 2 Presentation of the condition metrics (CMs), with their names and abbreviations, the bibliographic reference that originally created them and the country, a short description of each, their formulas, ecological attributes included, and original instructions.

CM and reference	Brief description of CM	Formulas	Ecological attributes	Original instructions
Habitat Evaluation Procedure (HEP) or Habitat Units (US) (US Fish and Wildlife Service 1980) – United States	Measures the quality of a habitat, assuming the supporting needs of key-species are strongly correlated to environmental variables, so their presence is an indicator of habitat quality.	HEP = Habitat Suitability Index × area of habitat	Habitat variables (which will vary according to the species, e.g. food and reproductive resources, population dynamics, and especially easily measurable physical, chemical and vegetation variables).	Calculated to each species separately (population level); only comparable within the same species. Species are chosen based on public interest, economic and/or ecological value.
Habitat Hectares (HH) (Parkes et al. 2003) – Australia	Measures the quality of a vegetation type, expressed as a percentage of the benchmark for each attribute. It usually includes 10 attributes of quality: 7 of site condition, and 3 of landscape context.	HH = (sum of quality attributes in % scores) × area of vegetation sampled	Large trees, tree (canopy) cover, understory components, cover of weeds, recruitment, organic litter, logs, patch size, neighborhood, distance to core area.	Calculated to each vegetation type separately (assemblage level); comparisons are usually within the same vegetation type, but they may be between different vegetation types.
Florida Wetland Condition Index (FWCI) (Reiss 2006) – United States	Measures the quality of wetlands, based on six attributes of macrophyte assemblage, each previously scored from 0 to 10. They are correlated with water and soil parameters and to the Landscape Development Intensity (LDI), a human-disturbance measure.	FWCI = sum of scores of the six macrophyte attributes	Tolerant indicator species, sensitive indicator species, exotic species, floristic quality assessment index (FQAI), native perennial species and wetland status species. Scores range from 0 to 10 (10 = benchmark), which is done partly based on expert opinion.	Calculated to each wetland separately (ecosystem level); it can be grouped and calculated in local or regional scales. Attributes included in FWCI were chosen according to correlation with the two LDI categories, which is based on nonrenewable energy use in each land use within a 100 m buffer around a wetland (landscape level).
Stream Ecological Valuation Method (SEV) (Neale, Auckland N.Z., Council 2011) – New Zealand	Measures the quality of streams, based on the 14 most important hydrological functions (attributes). Each stream is sampled for the 14 attributes and each generates a score through specific algorithms. Each stream receives one SEV score, the higher the better its condition.	SEV = mean of the 14 hydrological attribute scores	Natural flow regime, connectivity and complexity of floodplains, connectivity for species migrations and to groundwater, water temperature control, dissolved oxygen levels, organic matter input, in-stream particle retention, decontamination of pollutants, substrate and riparian conditions, aquatic physical conditions, riparian vegetation intactness, evaluation of fish and of invertebrate communities.	Calculated to each stream separately (ecosystem level); comparable among streams of the same type, but it may compare streams of different types, considering different benchmarks for each type.
Biodiversity Offsetting Pilots (BOP) (DEFRA 2012) –England (UK)	Measures the quality of a habitat based on its distinctiveness and condition. Each habitat is assigned a category of distinctiveness, low (2), medium (4) and high (6), and a category of poor (1), moderate (2) and good (3) condition (associated weights in parenthesis).	BOP = habitat distinctiveness × habitat condition × area (hectares) If the area has >1 habitat type: BOP = BOP_hab1 + BOP_hab2 + BOP_hab3 + …	Distinctiveness: all habitats of England are already categorized (DEFRA 2012 - Appendix 1), based on attributes such as species richness, diversity and rarity. Condition: attributes vary with habitat type, but focus on vegetation structure and composition. The measurements are described in the HLS Farm Environment Plan handbook.	Calculated to each habitat type or group of habitats (ecosystem level); it allows various comparisons and out-of-kind trades, but there should never be a trade-down and high distinctiveness habitats should have like-for-like trades. Distinctiveness levels may be reconsidered according to local characteristics.
Landscape Context Index (LCI) (MADS 2012) – Colombia	Measures the connectivity of a patch in a local landscape, calculating the percentage of habitat within a buffer of 500 m radius around the patch. As it is a simple metric, it is usually combined with others in offsetting (see Mandle et al. 2016).	LCI = (habitat total area × 100)/(500 m buffer total area)	Total amount of habitat inside the buffer.	Calculated to each habitat type separately (assemblage level) at the landscape scale; only comparable within the same habitat type. The LCI of an offset must be equal to or greater than the LCI of the impacted patches (landscape level).
Quality Hectare (QH) (Temple et al. 2012) – Switzerland	Measures the quality of a vegetation type, expressed as a percentage of the benchmark for each attribute. We show here the attributes authors used in their case study, but they may vary according to the context.	QH = % habitat quality (which is the sum of attributes' %) × area of vegetation assessed	General condition of the forest, signs of cutting, openings, agricultural areas, fires, observations of the vertical structure of the forest canopy level, % canopy cover.	Calculated to each vegetation type separately (assemblage level); comparable within the same vegetation type, but may be used in out-of-kind trades.

Table 2 (continued)

CM and reference	Brief description of CM	Formulas	Ecological attributes	Original instructions
Module Assessment Method (MAM) (Morandeau and Vilaysack 2012) – Switzerland	Measures the quality of an area before impact and its forecast scenario after offset. The area is divided in sectors, each evaluated based on a number of pre-established variables, the quality attributes (QA), scoring from 0.2 to 2. The number of QA varies.	Sector 1 (S1) = (QA1 × QA2 × (…) × QA7) × sector area MAM = S1 + S2 + (…) + Sn	Impact area: biotope age, environment quality, net function, natural dynamic, conservation degree, quality of species composition, exigent species. Offset area: restoration feasibility, environment quality, net function, natural dynamic, needed maintenance, biotope regional representativeness.	Sectors must be as similar as possible in vegetation structure and composition; comparisons are made between areas that may include different vegetation or ecosystem types (ecosystem level).
California Rapid Assessment Method for Wetlands (CRAM) (California Wetlands Monitoring Workgroup CWMW 2013) – United States	Measures the quality of wetlands, based on sub metrics (attributes) used to calculate 4 ecological classes: buffer and landscape context, hydrology, physical and biotic structure. The sub metrics are scored in 4 classes (12, 9, 6, 3); higher values represent better quality.	CRAM = mean of 4 ecological classes scores Class score = % the sub metrics' score is of maximum possible score for that class	Buffer and Landscape: stream corridor continuity, % of wetland with buffer, average buffer width, buffer condition. Hydrology: water source, hydroperiod, hydrologic connectivity. Physical Structure: structural patch richness, topographic complexity. Biotic Structure: number of plant layers, number of co-dominant species, % invasion, horizontal interspersion, vertical biotic structure (some are based on expert opinion).	Calculated to each wetland separately (ecosystem level); the sub metrics may vary among wetland types, so comparisons must be made among wetlands of the same type. Different types may be compared considering different benchmarks for each type.
Conservation Significance Index (CSI) (Virah-Sawmy et al. 2014) – Australia	Measures the conservation value of a site – its significance, through endemic and/or threatened species in a site relative to their remaining habitat area. The higher the index, the more significant is the site. Authors suggest it to be complementary to other habitat-quality metrics.	CSI = (number of endemic and/or threatened species/their remaining habitat area) × impacted area OR offset area	Number of endemic/threatened species in the region of interest and their remaining habitat area.	Calculated for endemic and/or threatened species (assemblage level), comparable among different regions.
Somerset Habitat Evaluation Procedure (SHEP) (Burrows 2014) – England (UK)	Measures the quality of a habitat based on the Habitat Suitability Index as HEP, but includes spatiality: the Density Bands are 3 radius sizes concentric zones, centered at where the species was recorded, proxies for species density and functional connectivity. HSI here includes habitat formation, management and surrounding matrix.	SHEP = (Habitat Suitability Index × Density Band value) × habitat area	Habitat variables (which will vary according to the focus species), quality of matrix, habitat formation and management, density band values.	Calculated to each species separately (population level); only comparable within the same species. Species are chosen based on public interest, economic and/or ecological value. Density Band vary from 3 - closer to 1 - further from the species record, based on expert opinion.
"Log response ratio of species richness" (LRR) (Spake et al. 2015) – England (UK)	Measures the quality (success) of restoration, by assessing the richness difference of functional groups (fungi, lichens and beetles) in secondary (restored) and old-growth forests. The old-growth richness is the benchmark for all groups, so the smaller the LRR, the better the quality.	LRR = (Ln mean richness in secondary forest) − (Ln mean richness in old-growth forest)	Richness of epiphytic lichens, ectomycorrhizal fungi, deadwood fungi, litter fungi, saproxylic beetles, non-saproxylic beetles (from coniferous and broadleaved forest).	Calculated to each functional group separately (assemblage level); only comparable within the same functional group; results are qualitatively analyzed in parallel.
Composite Biotope Value (CBV) (Pöll et al. 2016) – Austria	Measures the quality (success) of restoration, considering old-growth areas as the benchmark and accounting for gradients of equivalence. The area is divided in polygons to which a biotope type is attributed.	CBV = Biotope Type (BT) + (sum structural attributes) + (sum relevance attributes) + (sum managements) − (sum habitat threats)	BT: biotope restorability, rareness, complexity and species diversity, all based on expert opinion. Structural: diversity indices for biotope type and plant community diversity, % cover of a plant species, connectivity among habitat patches. Relevance: plant species present in Red List. Manage: current and target management activities. Threats: 6 most abundant threats to habitat.	Calculated to each biotope type separately (ecosystem level), the final CBV value must be compared to the benchmark to judge about the restoration. An average of different CBVs may be calculated to compare areas with more than 1 biotope type.

Table 2 (continued)

CM and reference	Brief description of CM	Formulas	Ecological attributes	Original instructions
NSW Vegetation Integrity Score (VIS) (OEH - Office of Environment and Heritage for the NSW Government 2017) – Australia	Measures the quality of a vegetation type based on the composition, structure and function of the "growth-form groups" (e.g. trees, shrubs, grass-like) of a site. Adapting the formula, it can predict the vegetation condition before and after impact offset implementation, either with or without management.	VIS = cubic root (CCS × SCS × FCS) CCS = sum (composition score × weight of all growth-form groups) SCS = sum (structure score × weight of all growth-form groups) FCS = sum (function score × weight of all attributes)	Composition Condition Score (CCS): Mean species richness for the growth-form group. Structure Condition Score (SCS): Mean cover for the growth-form group. Function Condition Score (FCS): mean number of large trees, mean length of fallen logs, mean litter cover, mean tree regeneration, mean tree stem size.	Calculated to a vegetation zone that may include different growth-form groups (ecosystem level), so it allows comparisons of different vegetation types. In cases of open-vegetation types, FCS is excluded from the metric's formula.
Ecosystem Services -based Soil Quality Index (SQUID) (Drobnik et al. 2018) – Switzerland	Measures the quality of ecosystem services (ES) based on soil functions and their capacity to support and provide the ES. There are up to 16 soil-based ES, ranging from 0 (soil supports ES poorly) to 5 (soil supports all ES highly). The higher the SQUID score, the higher the ES quality.	SQUID = mean of soil-based ES Soil-based ES = sum (soil function quality × function weight of all functions)	The 16 ES belong to 4 categories: healthy/wellbeing, security, natural diversity and natural production factors (economic services). Soil functions (10) are calculated based on 10 soil attributes. For more details, see Drobnik et al. (2018).	Calculated to a region, which may include different vegetation, habitat and ecosystem service types (ecosystem level), so it allows out-of-kind trades. Soil-function weights are provided by expert opinion.
"Disaggregated Model - Reef Habitat" (DMRH) (Stone et al. 2019) – Wales (UK)	Measures the quality of reef habitats through assessments of a focus species (*Sabellaria alveolata*). Based on the Disaggregated Model (Maseyk et al. 2016), in which components and attributes are chosen and measured separately and analyzed in conjunction. It seeks to evaluate the spatial-temporal influence on the condition of each site.	DMRH: C1 = % species cover C2 = abundance of associated species C3 = % formation of the 5 categories C4 = % tube aperture of the 5 categories	C1 species distribution: cover of *S. alveolata*. C2 species composition: abundance of species associated with *S. alveolata*. C3 species age structure: 5 categories of *S. alveolata* formation: hummock, sheet, reef, patchy and encrusting. C4 reef health: 4 categories of *S. alveolata* tube aperture condition: newly settled, crispy, worn and dead.	Calculated to each *S. alveolata* habitat separately (ecosystem level), comparable within this type of habitat, but trading-up is possible. The case study presented brought very specific attributes, but they should be chosen according to the conservation policy most adequate to the issue.
"Equivalent Connectivity Framework" (ECF) (Bergès et al. 2020) – France	Measures the quality of a landscape before and after impact and offset take place, in terms of functional connectivity – Equivalent Connectivity index (i.e. ECA - Saura et al. 2011). Scenarios are generated and compared with the goal of achieving a connectivity NNL.	ECF = variation in EC = ECafter – ECbefore EC = √sum of the dispersal probabilities between all pairs of patches in the landscape	Patch area, estimation of the focus species dispersal capacity (based on database and/or expert opinion). These attributes are multiplied for each pair of patches to result in the dispersal probability.	Calculated to each species separately (population level); comparisons among landscape scenarios are possible only for the same species.

Names in quotation marks were given by the authors in the lack of an official original name. These data help in answering questions 1, 2, 3 and 4. CMs are disposed in chronological order of creation.

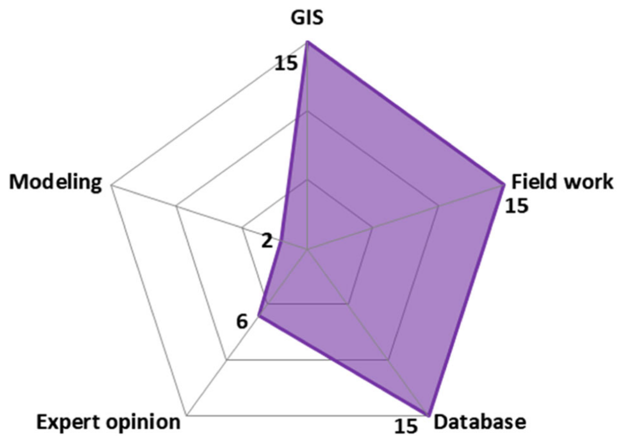

Fig. 3 Types of method and data required to calculate the condition metrics (CMs) reviewed. The numbers at the vertices of the colored polygon represent the number of CMs by data type. We highlight that often one CM demands more than one method or data type

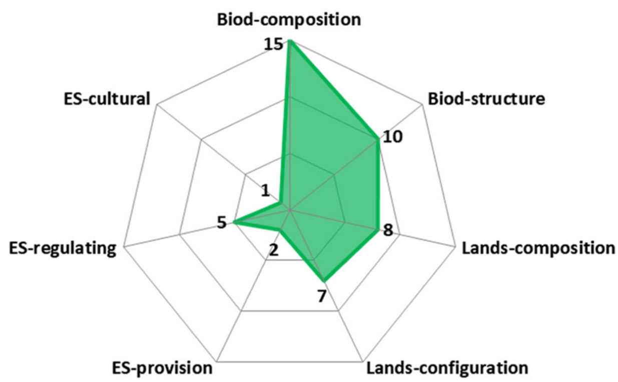

Fig. 4 Components of equivalence dimensions included in the condition metrics (CMs) reviewed. The numbers at the vertices of the colored polygon represent the number of CMs per component type. Biod biodiversity, Lands landscape, ES ecosystem services. We highlight that often one CM includes more than one component

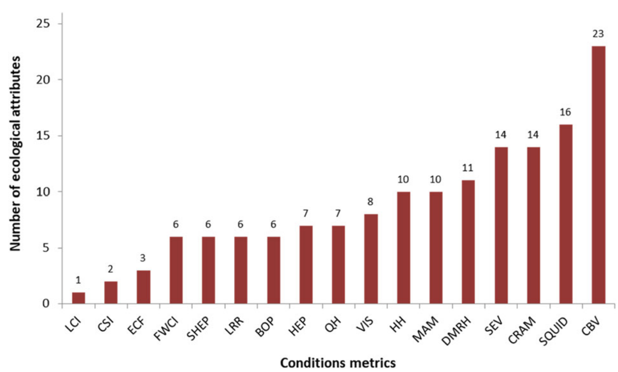

Fig. 5 Number of ecological attributes demanded by each condition metric (CM). On each bar is shown the exact number per metric. For CMs' abbreviation codes, see Table 2. We highlight that SHEP and HEP may demand a larger number of attributes, as they depend on the focus species on which the metric will be calculated, and BOP also may demand more attributes because it is originally presented with general attributes only (see Table 2)

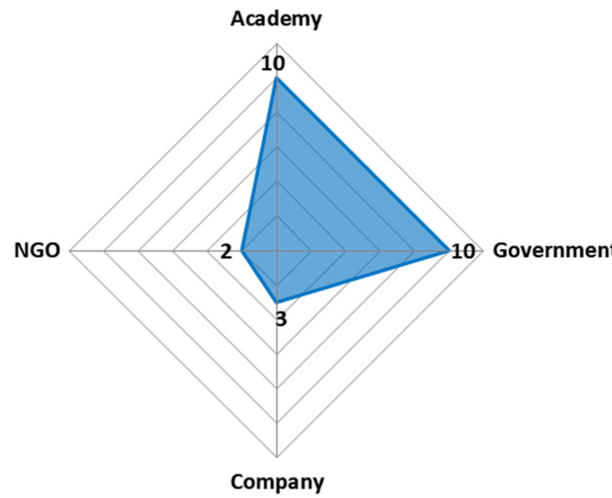

Fig. 6 Types of institutions that developed the condition metrics (CMs) reviewed. The numbers at the vertices of the shaded polygon represent the number of CMs that were developed by each institution (Academy, NGO, Company and Government). We highlight that often CM development happened in collaboration among institutions

in Brazil - Souza and Sánchez 2018). This heterogeneity is probably related to the great difference in offsetting implementation especially between the Global South and North (Gonçalves et al. 2015; GIBOP 2019). The absence of landscape attributes from the metrics may be due to their inclusion in the rules of offsetting – e.g. offset sites are required to have a similar landscape context as impact sites. In any case, our results indicate this concern is being addressed. Even though inclusion of connectivity issues is limited (Kujala et al. 2015) and cumulative landscape-scale impacts are still ignored in offset schemes (Tarabon et al. 2019), there are recent efforts to address this theme (e.g. Bergès et al. 2020). This is positive, since the species-specific landscape connectivity assessment can help ensure offsets contribute to species persistence in the landscape (Marshall et al. 2020a).

The ecosystem services dimension was seldom incorporated in CMs, in spite of calls for increased recognition of socio-environmental aspects in offset metrics (Griffiths et al. 2019; Mandle et al. 2015). This could partially be due to the way offsetting policies were initially designed, more focused on biodiversity and usually with no clear intent to incorporate compensation for ecosystem services (Mandle et al. 2015; Sonter et al. 2020; Souza et al. 2021). Besides, they can be hard to quantify, since supply and demand are often generated at different spatial scales, demands differ among stakeholders and assessing the actual delivery of service is difficult (Geijzendorffer and Roche 2014; Metzger et al. 2021). Recent works have addressed the gap between social and biodiversity factors in environmental impact assessment (Bull et al. 2018; Griffiths et al. 2019) and offsets (Souza et al. 2021). Engaging with local communities (Tengö et al. 2017), conducting early research on potential impacts on ES, and seeking synergies between ES offsetting and other biodiversity offset measures (Souza et al. 2021), may help encourage their inclusion in condition metrics and offsetting more generally. This inclusion would help identify the most appropriate offset strategy (Habib et al. 2013), thus improving offset implementation and effectiveness (Habib et al. 2013; Sonter et al. 2020).

Data Needs

The condition metrics reviewed are strongly underpinned by field measurements (or well-established databases). If on the one hand fieldwork may be expensive and time-consuming, on the other it improves offsets planning and implementation (Souza and Sánchez 2018), as knowing the present condition at impact and offset sites is required to conclude like-for-like offset trades (BBOP 2012a). GIS data were often used in CMs, whereas modeling and expert opinion are rarely used. However, GIS, modeling and expert opinion data could be explored more to enhance the inclusion of landscape and ecosystem services dimensions of equivalence in CMs. For example, GIS is already used in some CMs to calculate landscape metrics (California Wetlands Monitoring Workgroup CWMW 2013; Morandeau and Vilaysack 2012; Parkes et al. 2003); modeling could be used to spatialize and to infer information about those ecosystem services that are better-known, based on previous field studies (Bergamo et al. 2021); expert opinion and/or Traditional Ecological Knowledge could be used to choose which ecosystem service to analyze in a certain region according to its regional importance, or which landscape features are more important to an endangered species (Burrows 2014; Hill et al. 2020).

Many CMs combined a high number of ecological attributes. Still, most belonged to a single dimension, i.e. biodiversity, often limited to species richness and habitat structure assessments. Increasing the number of attributes in metrics can make their measurements not only more complex, as also harder to understand by practitioners and general public (Bezombes et al. 2017), besides being more time-consuming and expensive to compute (Bezombes et al. 2018; Quétier and Lavorel 2011). This could hamper the use of CMs, especially in regions where there is no consolidated database or limited funding to collect field data, such as some countries of the Global South (Magnusson et al. 2005; Magnusson et al. 2013). To include all the dimensions of equivalence (Gonçalves et al. 2015; Maseyk et al. 2016; Marshall et al. 2020a), while preventing a reduction of the information given by the metric (Quétier and Lavorel 2011), understanding the relationships among condition metrics' ecological attributes could help. Both trade-offs and synergies have been described for offset metrics (Bezombes et al. 2017; Gamarra et al. 2018; Sonter et al. 2020). Trade-offs among ecosystem services and biodiversity attributes have been acknowledged, and managing these trade-offs is important to include both dimensions in offsetting (Sonter et al. 2020; Souza et al. 2021). Further tests, e.g. correlation, could reveal whether the attributes hold some redundancy (Dormann et al. 2013), which could reduce the overall number of attributes in a CM without losing relevant information.

Disaggregated and Aggregated Metrics

Despite criticism of aggregated metrics (Hanford et al. 2017; Maseyk et al. 2016; Gonçalves et al. 2015), they predominate. This is probably because aggregation results in a single value to describe complex environmental elements, which is simple and easily communicated (Gardner et al. 2013; Maseyk et al. 2016), including with local communities affected either by impact or offset. Also, trades between sites may become easier and quicker, which benefits developers, as they are usually under time and cost constraints. Moreover, aggregation can be attractive as it increases flexibility in offsetting when no-net-loss for each separate ecological attribute is not a goal to be achieved. Aggregation may allow the condition metric value at a site to increase in different ways, since an increase in any one attribute could raise the metric final result.

Thus, aggregation may decrease the ecological equivalence of trades (Gibbons and Lindenmayer 2007; Hanford et al. 2017) and these possible consequences must be made clear. A disaggregated measurement framework allows greater visibility of what is being measured and what is being exchanged (Maseyk et al. 2016; Quétier and Lavorel 2011), enhancing the transparency of the offset process. Maseyk et al. (2016) described a disaggregated model for a loss-gain metric that accounts for each biodiversity attribute individually. This diminishes the complexity of calculations, as complex formulas are replaced by a series of simple metrics (Maseyk et al. 2016). Disaggregation is independent of the number of attributes included in a metric, so it remains a key recommendation when developing a condition metric (Hanford et al. 2017; Maseyk et al. 2016; Gonçalves et al. 2015). Hence, a disaggregated framework could serve as a base structure for a new condition metric.

The Dominance of the Global North Context in the Metrics Evaluated

Offset schemes are usually developed for a specific regional or local context (zu Ermgassen et al. 2019) and our results indicated the same for condition metrics. There is evidence that using different offset metrics in a given offset scheme can result in divergent amounts of estimated gains to achieve no net loss (Bull et al. 2014b; Söderqvist et al. 2021). Similarly, caution in transposing or adapting condition metrics among places is warranted (Bull et al. 2014b). In some cases, developing new CMs that are tailored to the specific environment the offset targets will be necessary. This may be especially relevant to Global South countries. Our results showed that almost all the CMs reviewed were created in Global North countries. Overall, Global South countries retain high biodiversity (Myers et al. 2000) and yet their offsetting schemes are still in early stages compared to the Global North (Gonçalves et al. 2015; GIBOP 2019) with no clear results yet (Reid et al. 2015; Bidaud et al. 2015). At the same time, they are the focus of substantial new development projects (Acosta 2016) and may be more vulnerable to economic pressures, which may result in greater damage to the environment (Virah-Sawmy et al. 2014). Currently, many Global South countries lack standardized metrics and procedures for compensation and offset schemes (Reid et al. 2015; Souza and Sánchez 2018). Therefore, caution in adapting CMs and creating new ones is particularly important in countries of the Global South.

Conclusions

Based on our findings, we recommend condition metrics should be adapted when transposed to new environments, or designed afresh to align with need, which may be more urgent in Global South countries. Adaption or creation should take into account the socio-environmental context of the area of interest. Testing for synergies and trade-offs among ecological attributes should help in using less attributes without losing information, aiming to capture the attributes containing more divergent information and exclude those found redundant. It could generate, for instance, a standardized group of attributes that could be used in situations where data availability is low or fieldwork is not possible. This, alongside with incremented use of GIS, modeling and expert opinion methods, could facilitate including the three dimensions of equivalence (biodiversity, landscape, and ecosystem services), which would enhance chances of reaching ecological equivalence. The dimensions should be presented in a disaggregated framework, permitting compensation of their components or attributes independently and more transparently. Some aggregation of attributes may be allowed, but its higher-level dimensions and components should remain disaggregated. This set of recommendations would contribute to fill the gaps in the metrics reviewed here and, at the same time, simplify these metrics without losing important information. This should substantially improve condition metrics contribution to achieve ecological equivalence and biodiversity no net loss in offsetting.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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