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PERSPECTIVE

Emerging Methods in Business and Biodiversity

Measurement approaches for corporate impacts on ecosystem condition: Current landscape and future priorities

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Abstract

1. Ecosystem condition is an important concept for understanding the impacts and dependencies of business on biodiversity and consideration of it is recommended by assessment and disclosure frameworks, including the Corporate Sustainability Reporting Directive, Taskforce on Nature-related Financial Disclosures (TNFD) and Global Reporting Initiative (GRI).
2. Approaches for measuring corporate impacts on ecosystem condition vary in their underlying methods and metrics. This creates uncertainty in their use by business. Here, we discuss the appropriateness of different approaches in different decision-making contexts, including the selection of appropriate reference conditions and granularity of metrics.
3. The assessment of company impacts on ecosystem condition should be seen as an iterative process with flexibility to continually improve approaches over time as new methods and data emerge to fill key knowledge gaps.

KEYWORDS
applied ecology, policy

1 | INTRODUCTION

Biodiversity is in rapid decline globally, and the private sector has a pivotal part to play in halting and reversing this loss (Ruckelshaus et al., 2020; Smith et al., 2020). Businesses assessing the impacts and dependencies of their value chains on biodiversity, setting transparent targets and taking evidence-based action are a priority for global policy (Mair et al., 2024).

Consensus is emerging on the value of assessing impacts and dependencies at the ecosystem level (Burgess et al., 2024; UNEP-WCMC, Capitals Coalition, Arcadis, ICF, WCMC Europe, 2022). Assessment at this level has many advantages. Firstly, distinct ecosystems are an important unit of biodiversity in themselves, and understanding impacts at this level is essential for obtaining a holistic understanding of impacts on biodiversity, beyond individual species (Nicholson et al., 2021). Secondly, it is often the interactions between species and their environment in functioning ecosystems that provide the ecosystem services upon which business and civil society depend (Birkhofer et al., 2015; La Notte et al., 2022). As such, impacts and dependencies at the ecosystem level are key components of voluntary and mandatory reporting initiatives such as the TNFD framework (Taskforce on Nature-related Financial Disclosures, 2023), the Corporate Sustainability Reporting Directive (European Commission, 2023), as well as the Global Reporting Initiative's (GRI) Biodiversity Topic Standard (Global Sustainability Standards Board, 2024).

Changes in ecosystems can be characterised in two ways: ecosystem extent, defined as changes in the area coverage of an ecosystem, and ecosystem condition, defined as the overall quality of an ecosystem quantified by metrics of abiotic and biotic characteristics (Czúcz et al., 2021). To capture both elements, surface area adjusted for condition is often used as a key metric for both environmental impact assessment (e.g. offset design for no-net-loss requirements) and corporate biodiversity footprint assessments and accounting (e.g. Endangered Wildlife Trust, 2020).

Methodologies for assessing impacts on ecosystem condition are often developed outside of the context of corporate assessments of impacts and dependencies specifically. For example, ecosystem extent and condition underpin the UN System of Environmental Economic Accounting (SEEA) Ecosystem Accounting framework (Edens et al., 2022), and indicators of ecosystem condition have been developed for policy reporting such as the Kunming-Montreal Global Biodiversity Framework (Nicholson et al., 2021). However, the development and implementation of business-focused methods for assessing corporate impacts on ecosystem condition are in their infancy (Zhu et al., 2024).

In measuring impacts on ecosystem condition, businesses may apply 'off the shelf' methodologies, frameworks and tools, or apply their principles and steps within bespoke measurement approaches. For clarity, here we define a 'measurement approach' for the purpose of assessing corporate impacts on ecosystem condition as 'the application of metrics of ecosystem condition to inform on the potential or actual impacts of business activities along the value chain'. These include:

- Methods of spatial analysis using metrics and data layers reflecting ecosystem condition (e.g. Venegas-Li et al., 2024)
- Model-based approaches for assessing impacts across the life cycle of products and services (e.g. CDC Biodiversité, 2023)
- Frameworks that guide the structuring, organisation and reporting of measurements of actual ecosystem state (via direct surveys or remote sensing) (e.g. Houdet et al., 2020)

In this paper, we build on concepts and principles outlined in UNEP-WCMC, Capitals Coalition, Arcadis, ICF, WCMC Europe (2023) to first identify the key aspects differentiating measurement approaches for corporate impacts on ecosystem condition. We discuss four core areas of methodological differentiation: coverage of condition elements, approach to setting reference conditions, underlying method for measuring condition and approach to attributing impacts. We reflect how these methodological differences influence their suitability for different decision-making contexts, before outlining key data and knowledge gaps and capacity building priorities for future development.

2 | POINTS OF METHODOLOGICAL DIVERGENCE IN MEASUREMENT APPROACHES

2.1 | Coverage of the different components of ecosystem condition

The UN SEEA-Ecosystem Accounting guidance suggests that measuring ecosystem condition entails identifying relevant characteristics, the development of indicators and metrics for those characteristics and aggregating such measures to assess overall condition (Czúcz et al., 2021). Characteristics are selected to cover the three core dimensions of ecosystem structure, composition and function as well as landscape structural characteristics (Carter et al., 2019; Czúcz et al., 2021; UNEP-WCMC, Capitals Coalition, Arcadis, ICF, WCMC Europe, 2022). Ecosystem structure indicators reflect aggregate biophysical properties of ecosystems, such as vegetation heights or seabed habitat complexity, irrespective of specific species composition. Structure at the landscape scale includes levels of fragmentation and connectivity (i.e. how linked patches of habitat are to one another). Composition indicators measure which species are present at the location and their relative abundances within an ecosystem. Lastly, function indicators measure a process that the ecosystem undertakes or reflects the capacity to perform these processes, for example, net primary production, water filtration.

An optimal methodology for assessing the biotic elements of condition is likely to cover characteristics across the core dimensions of structure, composition and function. Different measurement approaches, however, may vary in their weightings across these components. For example, commonly applied metrics by the private sector such as Mean Species Abundance (Schipper et al., 2020) and the Potentially Disappeared Fraction of species (PDF) (Huijbregts et al., 2017) only describe change in composition.

2.2 | Approach to reference conditions

To measure the condition of ecosystems, the variables reflecting ecosystem structure, composition and function are assessed compared to a reference condition to assess the degree of modification (Keith, Czúcz, et al., 2020; McNellie et al., 2020). Some examples of potential reference conditions include comparison to (1) the 'historical' condition (e.g. pre-industrial), (2) 'best-available' or 'least disturbed' condition (i.e. the highest condition example of an ecosystem type currently found), (3) 'contemporary' condition (the condition of an ecosystem at a period in its recent history for which data are available) or (4) 'undisturbed or minimally disturbed' (the condition of an intact ecosystem with maximum integrity and no or minimal levels of disturbance).

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Selecting reference conditions is inherently a value laden process, as an ecosystem in 'high condition' means different things to different stakeholders (Comte et al., 2020). For example, a state of an ecosystem that maximises its value in providing habitat for threatened species may not necessarily be the same as the state that maximises the delivery of ecosystem services. Both examples may not necessarily be the same as a historical 'pre-disturbance' ecosystem state largely free from human modification or management (Murcia et al., 2014; Prangel et al., 2023).

The approach applied to setting reference conditions infers what 'question' is being asked through ecosystem condition measurement within any given use case. Using condition measurement to ask 'What have been the losses and gains in the planet's natural ecosystems? (and in a business context, the 'footprint' of the business's activities on these ecosystems), is distinct from using condition measurement to ask, 'Is this area being used sustainably to maintain ecosystem service delivery?'

This distinction is particularly notable when measuring and reporting the impacts of anthropogenic land use systems owned or interacted with by a business (Figure 1). Some approaches and frameworks may consider land use systems such as cropland and pastureland as distinct ecosystem types alongside 'natural' ecosystems such as peatlands and grasslands (Petersen et al., 2022). This may lead to assessing impacts of these land uses against 'best available' examples of sustainable land management of these land use types. However, a 'footprint' measurement using

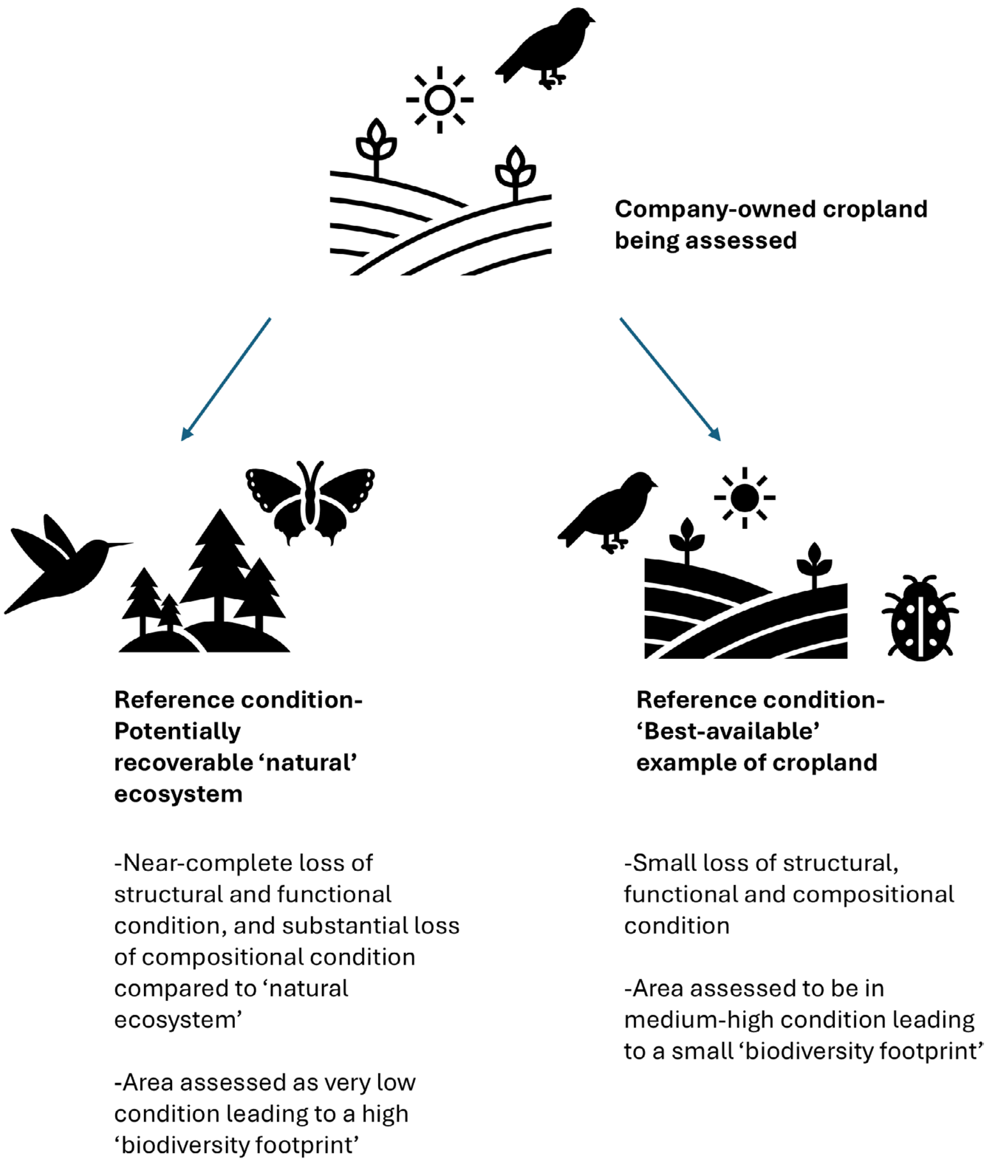

FIGURE 1 Implicit assumptions in different approaches to selecting a reference condition in a business context. The left-side approach enables the *full-scale assessment of changes in the state of ecosystems. The right-side approach* is best used for more sustainable land use management and not biodiversity footprinting as its application in a footprinting context may risk shifting baseline syndrome.

this approach to reference conditions would be relatively small and potentially misleading, risking shifting baseline syndrome (Papworth et al., 2009). Alternatively, assessing the condition of these land uses against the historic or potentially recoverable 'natural ecosystem type' within the areas would instead quantify the full amount of past losses in integrity of the ecosystem within the area. This would likely result in a much larger footprint.

2.3 | Method of measuring condition

The condition of ecosystems can be assessed through (1) directly measuring state variables that reflect condition through field surveys or remote sensing (e.g. Kotze et al., 2018; Suggitt et al., 2021), or (2) inferring state variables through the levels of pressures present (Hawkins et al., 2024; Katic et al., 2023) or (3) various combinations of both direct and inferred measurement (Figure 2). Inferring condition through pressures can range from metrics that map the distribution of pressures as a proxy for condition but do not assess the state of the ecosystem itself, to those that apply models that translate these pressures into estimates of composition, structure and function. For example, estimates of the impacts of different land uses have been obtained through the use of pressure-based modelling involving the PREDICTS database and the Biodiversity Intactness Index (BII) (Purvis et al., 2018) and the GLOBIO model and the Mean Species Abundance (MSA) (Schipper et al., 2020).

Approaches also differ in whether they measure and track (1) impacts on the condition of a realm generically (e.g. terrestrial realm, marine realm) by measuring characteristics that are not geographically linked with, or necessarily tailored to, a specific type of ecosystem (Rowland et al., 2018) or (2) impacts on the condition of specific biomes or ecosystem types (such as types of wetlands or forests), allowing the use of tailored metrics. For example, metrics reflecting change in species richness at a location reflect the composition element of ecosystem condition, but this metric is generic and applicable across all ecosystem types. At the opposite end of the scale, tracking the condition of individual 'ecosystem types' using tailored metrics (e.g. 'stand structure' for tropical forest ecosystems; Zhang et al., 2024) allows understanding of

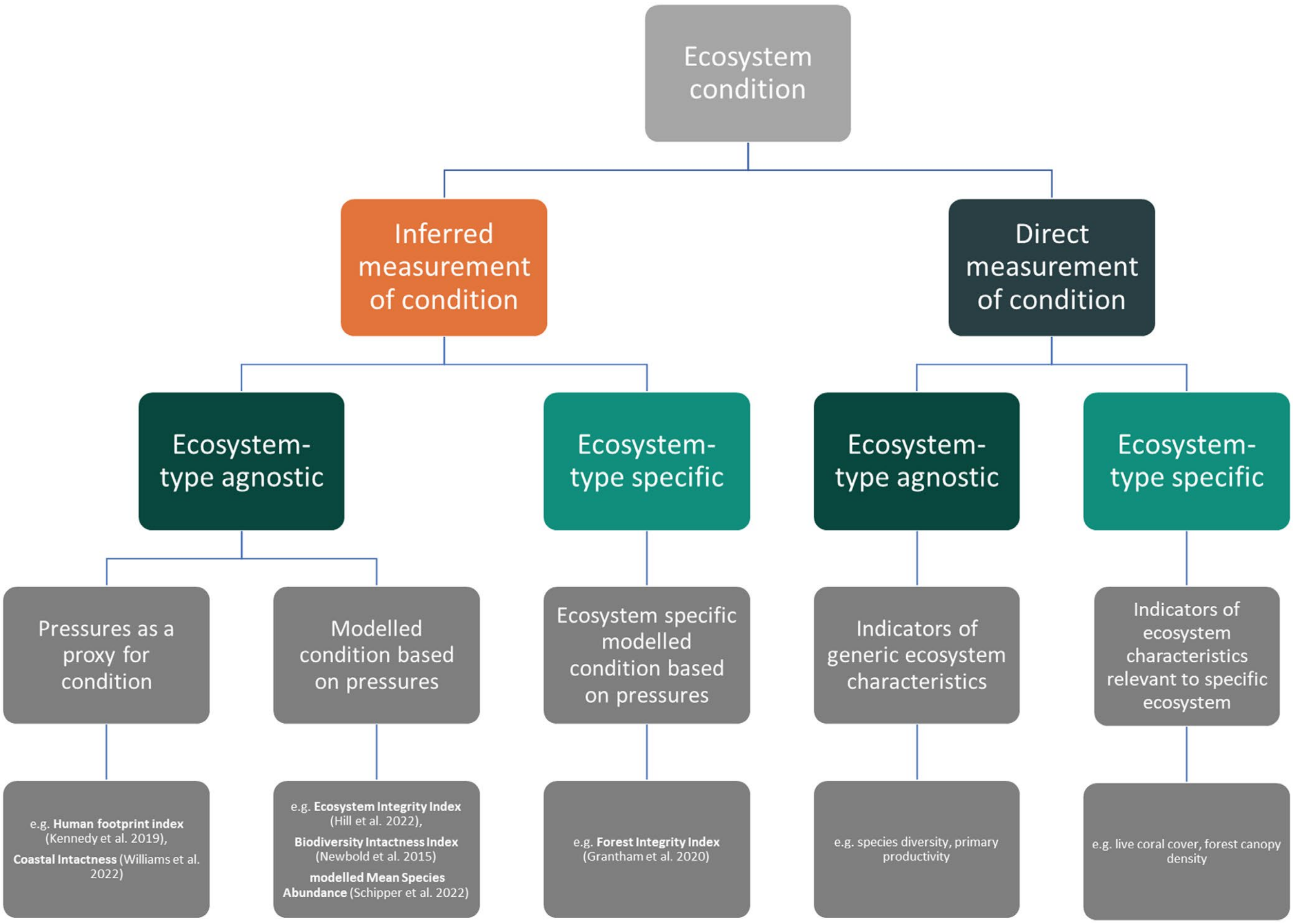

FIGURE 2 Typology of methods for measuring the ecosystem condition within an area, with a non-exhaustive list of example metrics within each category. Figure first published in UNEP-WCMC, Capitals Coalition, Arcadis, ICF, WCMC Europe (2023).

changes in characteristics that are most important for each ecosystem, where each may host unique species groups or provide specific ecosystem functions and services.

2.4 | Approach to attributing impacts to business activities

Methodologies for assessing the impacts of business on ecosystem condition vary in the mechanisms by which business activities are linked to changes in ecosystem condition.

Methods that directly measure ecosystem condition variables take a 'snapshot' of the residual ecosystem condition compared to the reference condition selected. In this sense, the condition measurements reflect the total negative impacts that have accumulated on that ecosystem in that location over time. They then build a time series of repeated 'snapshots' that enable assessments of periodic changes in condition. This is an especially important measure for businesses that directly own or steward an ecosystem asset (e.g. agri-business, forestry and other large landowners) for understanding the stocks of their natural assets.

To attribute changes in these stocks to business activities, measures need to be compared to a baseline state (e.g. pre-development state, or date the operation came into the ownership of the business). Attribution of the impacts since this baseline state to the business's activities is then observed or assumed based on the spatial proximity to business activities, or by combining measures of state changes with contextual information on pressures. However, actions of other actors at the location causing cumulative impacts, and/or natural drivers of change, may obscure clear attribution (Venier et al., 2021).

In contrast to spatial and temporal attribution, methods that model state based on pressures estimate the impacts of specific company pressures on ecosystem condition (Schmidt, 2008). In this sense, the resulting potential impact estimation is directly attributable to the business's activities. These methods, however, do not measure actual impacts on the ground and do not attribute observed changes in specific stocks to business activities.

Lastly, the approach to attribution adopted by many Life Cycle Assessment methods is to integrate a temporal dimension into models to evaluate how pressures applied at the period being assessed cause impacts on condition over their 'lifetime' (Winter et al., 2017). For example, by expressing impacts in species loss over an area over a year. Therefore, unlike other methods, a 'snapshot' of ecosystem condition is not made for a specific point in time. This means that while these life cycle assessment models are useful for understanding the potential impacts of activities, they do not allow a time series of accumulated changes in an ecosystem to be built.

Trade-offs therefore exist between more direct measurement-based approaches, model-based approaches and those that integrate a temporal dimension between accuracy and precision on the one hand, and the ability to attribute impacts to specific activities on the other.

3 | LINKING MEASUREMENT APPROACHES TO DECISION-MAKING

The variation in methods for assessing impacts on condition means that some are likely more suitable for certain types of decision-making than others.

3.1 | High-level screening of potential impacts on ecosystem condition

Screening processes seek to identify 'hotspots' of potential impacts across multiple sites, business operations and value chains, to identify areas for more in-depth assessment and strategy formation. It is this initial step where methods that apply model-based approaches to estimate potential impacts are likely to be most suitable, where the ability to apply the approach rapidly at scale takes priority over accuracy and spatial precision. To make rapid comparisons of potential footprints on ecosystem condition at different locations, realm-level metrics such as modelled Mean Species Abundance are often applied where impacts are expressed generically on the whole terrestrial or marine realm without tailoring to specific ecosystem types. Information on these potential impacts can be combined with information on the sensitivity of locations to aid prioritisation, such as ecosystem threat status (Keith et al., 2015). These model-based approaches may also support decision-making associated with how to reduce potential impacts.

3.2 | Tracking actual impacts over time

In contrast to high-level screening, tracking observed impacts on ecosystem condition at specific locations of operation is required for understanding actual impacts, evaluating the effectiveness of management strategies and robust reporting and disclosure of material impacts at locations. Tracking actual impacts requires more directly observed 'on the ground' assessments of ecosystem condition than high-level screening of potential impacts.

The most granular assessment of impacts in this context will track impacts on specific ecosystem types, rather than measuring impacts only at the realm level (Houdet & Teren, 2022). Tracking impacts on specific ecosystem types helps ensure ecological equivalency in reported impacts, where negative impacts on one ecosystem type are not 'balanced' by positive impacts on a different ecosystem type. Retaining ecological equivalency is particularly important when assessing achievement of 'no net loss/net gain' based targets (Czúcz et al., 2025).

Corporate biodiversity accounting frameworks, such as the Biological Diversity Protocol (Endangered Wildlife Trust, 2020), are emerging to support structuring and organising biodiversity metrics using accounting principles, including ecosystem condition, to track business impacts over time and produce robust biodiversity footprints. Compiling information on ecosystem extent and condition at locations of operations in an asset register is key to these accounting frameworks. Updating extent and condition assessments within this asset register and using principles of double-entry bookkeeping applied in financial accounting allows for accounting statements to be produced.

4 | FUTURE RESEARCH AND CAPACITY BUILDING PRIORITIES

The measurement of corporate impacts on ecosystem condition is a rapidly evolving field. Key technical gaps are hindering the full uptake of robust measurement approaches by the private sector. Below, we outline six research priorities, grouped around data and knowledge gaps, method development and capacity building.

4.1 | Data and knowledge gaps

4.1.1 | Availability of spatial data on ecosystem typologies

For businesses to assess impacts on specific ecosystem types, foundational information on those present along value chains is required. However, the lack of consistently applied ecosystem typologies and associated spatial data layers may hinder this more detailed level of assessment. Initiatives such as the IUCN Global Ecosystem Typology aim to provide a consistent approach to classifying ecosystem types. However, spatial data of the distribution and extent of different ecosystem types is patchy (Burgess et al., 2024; Keith, Czúcz, et al., 2020). Initiatives, including the Global Ecosystem Atlas by the Group on Earth Observations (GEO), are aiming to fill this crucial data gap.

4.1.2 | Data on marine ecosystem condition

Substantial knowledge gaps exist in measuring corporate impacts on marine ecosystem condition. There is therefore a need to evolve understanding of terrestrial reference conditions and attribution of impacts for the marine realm. Notably, data on condition variables are scarcer in the marine realm, delineations of distinct ecosystem types are less clear, drivers of change are more complex to attribute and spatial scales of impacts are much wider and more displaced (Cummins et al., 2023; Smit et al., 2021).

4.1.3 | Links between ecosystem condition and ecosystem service provision

An advantage of measuring impacts at the ecosystem level is the link between the condition of an ecosystem and its capacity to provide ecosystem services. However, in practice, the link between condition and service provision is variable and context specific, where low condition ecosystems may still maintain multiple ecosystem services (Rendon et al., 2022; Smith et al., 2017). Furthermore, often maximising the supply of some ecosystem services (e.g. logging and farming) can lead to further biodiversity losses and a decline in other ecosystem services (i.e. trade-offs between various consumption uses and conservation; Martini et al., 2024). Further research on characterising these links will make it easier to calculate the consequences of impacts on ecosystem condition in terms of potential disruptions to ecosystem services.

4.2 | Method development priorities

4.2.1 | Increasing coverage of pressure-state models

For risk screening applications, approaches that model potential impacts on ecosystem condition can be used to assess potential impacts of business activities. Underlying these models are on-the-ground data on how ecosystem condition responds to different types of anthropogenic pressures (Newbold et al., 2015). The scope and coverage of these methods therefore are directly related to the availability of data underpinning models. For example, while there is good availability of data for understanding impacts of land uses such as cropland and forestry, data for more site-based land uses such as energy and extractives are less available. Efforts to provide transparent and well-documented modelled factors for these land uses, as well as other pressures, such as fragmentation, pollution and invasive species, will increase the coverage of these model-based methodologies (Souza et al., 2015).

4.2.2 | Library of approved appropriate condition rating methodologies

The most precise measurement approaches of impacts on ecosystem condition apply 'on the ground' measurement tailored to specific ecosystem types (Houdet et al., 2020). Where possible, methodologies approved within local jurisdictions (e.g. as part of the permitting process) that clearly define appropriate reference conditions should be applied. However, the availability of these methodologies is inconsistent and lacking for many ecosystem types. Building a central database of simple and readily applicable methods for ecosystems globally could provide both consistency and robustness to corporate measurement.

4.3 | Capacity building

4.3.1 | Improved traceability of business activities

A commonly cited barrier to location-specific assessments of corporate impacts is a lack of traceability of business assets and value chains. (Beck-O'Brien & Bringezu, 2021). Ensuring capacity for accurate spatial mapping of business operations and assets, as well as improved traceability across complex global value chains, is required to be able to link business impacts to specific ecosystem types or apply more spatially refined characterisation factors within Life Cycle Assessments (Chaplin-Kramer et al., 2017).

4.3.2 | Accelerating uptake of corporate biodiversity accounting

Capacity building efforts to accelerate and scale the uptake of accounting frameworks for corporate biodiversity impacts that result in their application at scale can support standardising corporate assessments of impacts on ecosystem condition and ensure robust disclosures at priority locations.

5 | CONCLUSIONS

This paper has outlined the diverse approaches that can be taken to assess impacts on ecosystem condition while recognising that diversity also exists in the business decision-making contexts that they can be used for. It is important that emerging technical consensus on measurement of ecosystem condition translates into practical guidance within key corporate assessment and disclosure frameworks (including CSRD, TNFD and GRI) that allows for convergence and streamlining of these approaches between different frameworks. Furthermore, it is integral that future scientific developments in measurement approaches have these decision-making contexts in mind and target knowledge gaps that are most critical for scaling the uptake of ecosystem condition concepts in business nature strategies.

AUTHOR CONTRIBUTIONS

Jacob Bedford conceived the outline and led the writing of the manuscript. Joël Robert Auguste Houdet and Joshua Berger led ideation and writing on specific sections. Annelisa Grigg, Michelle Harrison, Emma Calhoun and Sharon Brooks contributed critically to the drafts and inputted on ideation and editing. All authors gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

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No data were used or produced for this perspectives paper.

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