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Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context

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A B S T R A C T

Global biodiversity is in rapid decline and halting biodiversity loss is one of the most important challenges humanity must tackle now and in the immediate future. The five main direct drivers of biodiversity loss are climate change, pollution, land use, overexploitation of resources and the spread of invasive species, which result from indirect drivers such as unsustainable production and consumption. It is therefore of paramount importance that scientifically robust methods are developed to capture impacts on biodiversity from a value-chain perspective. Life Cycle Assessment (LCA) methodology allows to quantify the impact of products and organisations throughout their whole life cycle. In the LCA framework, several methods for biodiversity impact assessment have been developed. Building on previous reviews, this article aims to critically analyse methods and models for biodiversity impact assessment in LCA and beyond as comprehensively as possible, and to select those that may be most suitable for application in an LCA context. 64 methods were reviewed and 23 were selected for a detailed analysis based on availability of documentation, domain of application, geographical scope, potential to be used in LCA, and added value. The analysis addressed their goal and scope, data use and needs, and impact assessment characteristics, revealing strengths and weaknesses of the methods. There is currently no method that takes well into account at the same time the variety of pressures on biodiversity, ecosystems, taxonomic groups, essential biodiversity variables classes, and the fundamental aspects to consider in biodiversity impact assessments – but for each of these five criteria, we show which methods perform best. For the future development of biodiversity impact assessment, it is required to improve the coverage of drivers of biodiversity loss, increase ecosystem and taxonomic coverage, include the assessment of ecosystem services, and develop robust indicators that allow for complementary analysis of more essential biodiversity aspects.

1. Introduction

While conservation biologists have been concerned with the impacts of human activities on biodiversity since decades (Soulé, 1985), biodiversity loss is increasingly being recognized as one of the top risks that humanity is facing by a variety of actors (United Nations, 2020; Robuchon et al., 2021; WEF, 2023). According to recent major global biodiversity assessments (IPBES, 2019; WWF, 2020), global biodiversity is in steep decline and it represents one of the planetary boundaries transgressed to the extent to which irreversible losses are already in place (Mace et al., 2014). This decline holds true for all biodiversity levels: ecosystems, species, and genes (Purvis et al., 2019). At the ecosystem level, since 2000, 1.9 million square km of wild and undeveloped land has been lost through conversion due to exponential growth in global trade, consumption and human population growth, as well as an enormous move towards urbanisation (WWF, 2020). At the species level, population sizes of mammals, birds, amphibians, reptiles, and fish have decreased by 68% in average between 1970 and 2016. Such population declines may in turn result in irreversible species extinctions, and the current rate of species extinctions is 10 to 100 times higher to the highest rate of the last 10 million years (Ceballos et al., 2015; Pimm et al., 2014). Finally, genetic diversity within species is estimated to have declined by 6% since the beginning of the industrial revolution (Leigh et al., 2019). Apart from change in land use, the other main direct drivers for biodiversity loss include resource overexploitation, invasive species, climate change and pollution (Millennium Ecosystem Assessment, 2005). Besides, biodiversity loss is not merely an environmental concern, as it also has important consequences on worldwide socioeconomic systems

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(Maier et al., 2019).

Against this backdrop, recent biodiversity policies recognize the need of protecting biodiversity by a whole-of-society approach. At the EU level, the European Commission (EC) has published the EU Biodiversity Strategy for 2030 (European Commission, 2020a) which highlights the need to better integrate biodiversity considerations into public and business decision-making at all levels, and commits to the development of methods, criteria and standards to measure the environmental footprint of products and organisations on the environment, including the use of life-cycle approaches and natural capital accounting. At the international level, the 196 Parties to the Convention on Biological Diversity (CBD) adopted in December 2022 the Kunming-Montreal Global Biodiversity Framework (CBD, 2022), which stresses the need to take measures to encourage and enable business to regularly monitor, assess, and transparently disclose their risks, dependencies and impacts on biodiversity along their value chains.

To assess biodiversity impacts of products and organisations, it is of paramount importance that scientifically robust models and indicators are developed to capture impacts on biodiversity from a value-chain perspective, enabling businesses to identify drivers of biodiversity loss, as well as to monitor evolution of impacts and to design mitigation strategies to be put in place (Neveux et al., 2018; Crenna et al., 2020). In the field of life cycle assessment (LCA), several models and methods (i.e. collection of impact assessment models) have been developed to assess biodiversity loss. Crenna et al. (2020) reviewed approaches for the impact assessment of products' and services' value chains on biodiversity in LCA, making a distinction between operational and non-operational models and methods. The former are available in LCA software, and are already widely used by LCA practitioners, whilst the latter are not. Crenna et al. (2020) highlighted that the existing metrics of biodiversity impact assessment in LCA are poor at capturing the complexities of biodiversity or are not fully operational to be used by LCA practitioners. This shows that the current LCA framework is not yet sufficient to support decision-making based on available biodiversity indicators.

Since the review of Crenna et al. (2020) was conducted, many new proposals to assess biodiversity impacts have been published. Because of this constant development, an initiative of the EC, the EU Business @ Biodiversity Platform, was set up to discuss the links between business and biodiversity at the EU level and to bring together a number of different methods adopted by different organisations (European Commission, 2020b). The platform published its third update report of the series "Assessment of Biodiversity Measurement Approaches for Businesses and Financial Institutions" (Lammerant et al., 2021). In this report, the Biodiversity Measurement Navigation Wheel is presented, which is a pragmatic decision framework to select the most suitable measurement approaches for a specific business context. The framework considers 19 methods to assess biodiversity impacts of businesses, whether they are companies or financial institutions. Several of these methods are also presented in a review paper by the United Nations Environmental Programme (UNEP) and World Conservation Monitoring Centre (WCMC) (UNEP – WCMC, 2020). UNEP – WCMC (2020) identifies at least twelve different biodiversity measurement approaches developed to answer different business needs or applications, e.g. to assess current or past performance, or to compare products. Crenna et al. (2020) have also analysed some of the methods mentioned by Lammerant et al. (2021) and in UNEP – WCMC (2020), e.g. Global Biodiversity Score, Biodiversity Impact Metric and Product Biodiversity Footprint, which the authors designated as 'beyond-LCA' methods, i.e. other approaches that follow life cycle thinking and ecosystem service accounting approaches. They concluded that many approaches make use of Life Cycle Impact Assessment (LCIA) methods and input–output databases, being generally coupled with other biodiversity metrics. Finally, assessing impacts and dependencies of business on biodiversity is also the focus of other Natural Capital Accounting (NCA) initiatives.

There has been an increasing interest to address biodiversity impacts, thus many new models and methods have been published recently. Building on existing reviews (Crenna et al., 2020; Lammerant et al., 2021; UNEP – WCMC, 2020; Winter et al., 2017; Curran et al., 2016), this paper include also the most recent models and methods to address impacts on biodiversity including those developed in the context of Natural Capital Accounting (NCA) initiatives. Importantly, this study also includes an aspect that was only partially covered in the previous review studies: how well biodiversity is taken into account in the different methods. This is addressed by analysing for each method how many pressures, type of ecosystems, taxonomic groups, essential biodiversity variable classes (EBVs), and fundamental biodiversity aspects it considers. The objective of this study is thus to analyse the progress in the development of models and methods for the analysis of biodiversity impacts in the LCA context and beyond, and to explore complementarities and completeness of LCA and beyond-LCA approaches.

With this paper we aim to facilitate the implementation of the EU Biodiversity Strategy in supporting the integration of biodiversity into value chains assessment. This work can inform the ongoing discussions related to the EC LCA methods – the Product Environmental Footprint (PEF) and the Organization Environmental Footprint (OEF) – on the best approaches to consider impacts on biodiversity (European Commission, 2021).

2. Materials and methods

A literature review was conducted on the latest advancements in biodiversity assessment in LCA, along with a large number of beyond-LCA models and methods. As described in section 2.1, existing approaches were then selected to be analysed in detail against a set of criteria reflecting their placement into or adaptability to the LCA framework (section 2.2).

As the studies collected were obtained from different disciplines (ecology, conservation biology, NCA, and LCA) and different terms might be used to refer to the same issue, we have included in Table 1 the definitions used throughout the article. For example, the term 'pressure' used in the manuscript refers to resources (e.g. land, water) and emissions (e.g. greenhouse gases), information typically collected in the Life Cycle Inventory phase, whereas the drivers are represented by human activities producing the pressures. In ecology and conservation biology, drivers are closer to the LCA concept of pressure. For instance, the Millenium Ecosystem Assessment (2005) identifies climate change, habitat change, pollution, invasive alien species, and overexploitation as direct drivers of biodiversity loss.

2.1. Screening and selection of the methods

An extensive bibliographic review on peer reviewed articles and grey literature was carried out in 2021–2023. A search was performed on the Scopus® database (Scopus, 2021) to derive an initial list of literature references aligned with the goal of the study using the following keywords: "LCA", "Life cycle assessment", "biodiversity", "ecosystem", "impact assessment". As this work builds on a previous review by Crenna et al. (2020), relevant papers cited in that review were added to the papers selected through the Scopus® database search. The references of the collected papers were carefully analysed in view of including any other mentioned relevant study which was not part of the references gathered, and complemented with references of current recommendations (e.g. from UNEP, 2016 and FAO, 2020), or reported in Lammerant et al. (2021), UNEP – WCMC (2020), Winter et al. (2017) and Curran et al. (2016). Moreover, as some of the methods are currently being developed and publications are not yet available, websites and webinars related to biodiversity were also used to harvest information.

The approaches identified were then analysed according to their application (e.g. company, product, territory), aim, system boundary, biodiversity impact assessment method or model, and indicators. Besides providing a comprehensive overview of currently known approaches for biodiversity assessment, this information allowed us to

Table 1
Definitions used throughout the article.

Term	Definitions
Driving Force/Driver:	Driving forces/drivers are activities and processes along the life cycle of the production and consumption systems causing pressures.
Pressure:	The physical result of a driving force that affects the state of the environment, as the use of environmental resources or the emission in the environment (elementary flows).
Reference state:	The state of ecological integrity against which the biodiversity performance is compared.
Impact:	A change in the physical, chemical, or biological state of the environment which determines a modification in quality of ecosystems and the welfare of human beings.
Baseline:	The starting point of the accounting or measurement process.
Inventory:	A collection of input/output data about the system being studied. It involves collection of the data (elementary flows) necessary to meet the goals of the defined study.
Impact category:	An impact category groups different emissions into one effect on the environment unit based on an impact assessment model taking into account the cause-effect chain of impact potential of each environmental pressure.
Impact assessment method and model:	An impact assessment method is a collection of individual characterization models addressing the different impact categories, which are included in the method.
Characterization factor:	A factor derived from a characterization model which is applied to convert an assigned life cycle inventory flow to the common unit of the impact category indicator.
Midpoint method:	An impact assessment method that provides indicators for comparison of environmental impacts at an early stage of the cause-effect chain between emissions (or resource consumption) towards endpoint level (e.g. climate change in CO_2 equivalents).
Endpoint method:	The category endpoint is an attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern. Hence, an endpoint method/model provides indicators at the level or close to Areas of Protection (ecosystem quality, human health, resources), at the final stage of the cause-effect chain (e.g. species loss).

determine which ones to include in a detailed analysis for applicability in LCA.

From the literature collected, some methods were not considered further. Reasons for the exclusion were (Fig. 1): 1) sufficient documentation was not available; 2) method did not show potential to be used in LCA (e.g. not including applicable impact assessment model, not showing potential for characterization factors development); 3) the geographical scope was too narrow (e.g. applicable to one country only); 4) the application domain/object was not on product, value chain, or company, and 5) method did not bring any additional aspect to LCA (e.g. impact assessment model was already operational in LCA, without any additional modelled impact mechanism or metric). The methods falling into one or several of these five categories were excluded from further analysis. All identified methods with brief description, and the exclusion criteria applied, can be found in SI.

2.2. Detailed analysis

The selected methods were analysed from an LCA perspective, focusing on 1) the goal and scope of the method; 2) the data used in the method; 3) impact assessment related aspects (Table 2). Goal and scope analysis includes aim of the method, system boundary describing the included life cycle stages, reference state and baseline descriptions, and whether the method is suggested for NCA. Reference state refers to the state of ecological integrity, which is used to compare biodiversity performance, while baseline is the starting point of the accounting or measurement process.

Data analysis includes the data used in the method describing the models, databases and other data sources used in the impact assessment or for defining the biodiversity value of reference state, as well as data on product and/or process to be used for performing the biodiversity assessment. Data on product and/or process can be divided to primary and secondary data. Primary data refers to company specific data, while secondary data can be used the complement the primary data when product/company specific data is not available.

Impact assessment analysis includes the inventory of the pressures, ecosystems and impact indicators included by the methods, impact assessment methods and models used to assess the impacts originated by the pressures, including analysis of the considered species groups, biodiversity impact metric(s) used in the method to express endpoint impacts, as well as Essential Biodiversity Variable (EBV) classes considered by the method. EBVs (Pereira et al., 2013) use six broad classes to measure biodiversity and biodiversity impacts, describing biodiversity at the level of genes (genetic composition), species (species populations, species traits), communities (community composition) and ecosystems (ecosystem functioning, ecosystem structure). Each impact assessment indicator included in the methods were assigned to EBV classes to highlight which aspects of biodiversity are considered. The metric used to characterise biodiversity impact may correspond to one single EBV or integrate several ones.

After analysing the aspects presented in Table 2, the methods were classified either as 1) LCA-based, those that use LCIA models in the impact assessment phase; or 2) beyond-LCA, those that use LCIA models complemented with other approaches beyond LCA or use only models beyond LCA in the impact assessment phase.

Furthermore, we evaluated how well biodiversity is taken into account in the different methods according to the following elements:

1) Pressures included in the methods, classified to align with the five main direct drivers of biodiversity loss according to Millenium Ecosystem Assessment (2005)
2) Ecosystems included in the methods
3) Taxonomic groups included in the methods
4) EBV class(es) considered into the metric(s) used to express biodiversity impact
5) Whether the approach can capture biodiversity impacts in terms of ecosystem-multifunctionality and/or global, irreversible species extinctions, as these have been recommended as the two fundamental aspects to consider when assessing biodiversity impacts in LCA (Marques et al., 2021). Ecosystem multifunctionality is the functioning of multiple ecosystem processes which are underpinned by local biodiversity, such as species with high local biomass or abundance (Grime, 1998); maintaining healthy multi-functional ecosystems permit to keep the ability of biodiversity to deliver a huge range of benefits to people (Millenium Ecosystem Assessment, 2005; Díaz et al., 2018). Global species extinctions correspond to the pruning of leaves in the tree of life, which currently threaten an estimated one million animal and plant species globally and represent irreversible loss when they happen (Díaz et al., 2019). Following Marques et al. (2021) and references therein, we considered that approaches that document impact on species abundances are able to capture biodiversity impacts in terms of ecosystem multifunctionality, and that approaches that model a potentially disappeared fraction regionally and aggregate the results globally are able to approximate biodiversity impacts in terms of global species extinctions.

Importantly, while some of the species groups described in the reference methods could be easily linked to taxonomic groups, such as mammals, birds or amphibians, some others corresponded more to

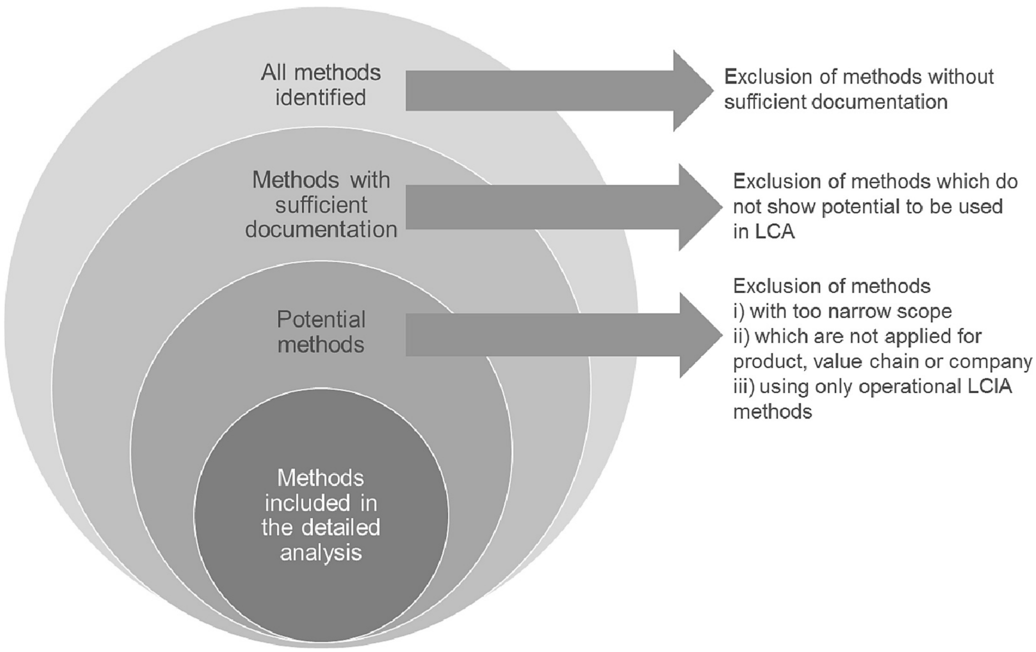

Fig. 1. Selection of methods included in the detailed analysis.

Table 2
Elements considered in the detailed analysis.

Criteria	Sub-criteria
Goal and scope	1. Aim of the method 2. System boundary 3. Reference state 4. Baseline 5. Whether the method is suggested for Natural Capital Accounting (NCA)
Data	1. Data used in the method 2. Data on product/process, including - primary data - secondary data
Impact assessment	1. Pressures included in the method (elementary flows modelled) 2. Ecosystems included in the method 3. Impact indicators included in the method 4. Impact assessment methods and models used to assess the impacts originated by the pressures 5. Biodiversity impact metric(s) in which the endpoint results are expressed 6. Essential Biodiversity Variable (EBV) classes

functional species groups, such as macroinvertebrates, zooplankton or algae, and could therefore not be unambiguously attributed to taxonomic groups. These latter were therefore categorised as 'other' in our completeness assessment.

For each method, we screened which categories of pressures, ecosystems, taxonomic groups, EBV classes, and fundamental aspects it addresses. Based on this screening, we highlighted for each of these criteria the percentage of categories that each method covers. It is worth bearing in mind for the interpretation of results that it is not because a method addresses one category that it implies a full coverage of the corresponding category. For instance, for the "taxonomic groups" criterion, a method addressing arthropods as one category of the taxonomic groups does not imply that all arthropod classes are covered.

3. Results and discussion

This section presents the results of the screening and selection of the methods (section 3.1), and the results of the detailed analysis (section 3.2).

3.1. Screening and selection

In the screening step, 64 models and methods were identified (complete list in SI, Table 1), including five operational LCIA methods identified by Crenna et al. (2020). From those 64 methods, 16 were excluded from the detailed analysis because they did not show potential to be used in the LCA framework; eleven t because the domain of application was not on product, supply chain, or company; and four due to lack of sufficient documentation. Four methods were excluded because they did not provide any additional aspect to LCA, i.e. the method uses operational LCIA model, or makes use of pre-existing biodiversity analysis methods and databases without any additional aspects, e.g. in the case of the Bioscope tool (Platform BEE, 2016), geoFootprint (Reinhard et al., 2021) and the Biodiversity Footprint for Financial Institutions (Broer et al., 2021), which use either ReCiPe or Impact World+ without any modification.

In addition, six methods were excluded because they are currently at a stage of development that does not allow for their application in the short to medium term (e.g. characterization factors for only one country with considerable effort for extension, empirical data on a limited set of locations, etc.). These include the models developed by Dorber et al. (2019), Turgeon et al. (2021) and Trottier et al. (2021) on the impact of hydropower, the model of Woods and Verones (2019) on the impact of human disturbance on seabed, and the model of May et al. (2021) on bird diversity impacts due to wind energy.

Finally, 23 methods were retained for a detailed analysis (Table **3**). A code (# X) was attributed to each one, where # is the number and X the short name as attributed in Table **3**. For simplicity, the approaches are referred to in the text using this code. For example, the Biodiversity Value method in Table **3** is referred as *#6 BV*.

According to the classification described in section 2.2, the models and methods in Table **3** are grouped as follows:

- 17 LCA-based, which use LCIA models in the impact assessment phase (*#1–17*), including operational LCIA methods identified in previous review,

Table 3
Biodiversity assessment models and methods selected for detailed analysis from the 64 approaches identified in the literature review.

#	Method name (short name)	Type	Reference
1	ReCiPe 2016 (ReCiPe)[1]	LCA	Huijbregts et al., 2016, Huijbregts et al., 2017)
2	LC-Impact (LC-Impact)[1]	LCA	Verones et al., 2016, Verones et al., 2010)
3	Impact World+ (IW+)[1]	LCA	Bulle et al. (2019)
4	Stepwise2006 (SWise)[1]	LCA	Weidema et al. (2008), Weidema (2009)
5	EcoScarcity 2013 (EcoS)[1]	LCA	Frischknecht and Büsser Knöpfel (2014)
6	Biodiversity Value (BV)	LCA	Lindner et al. (2019)
7	Land Use Impacts on Functional Plant Diversity (FPD)	LCA	Scherer et al. (2020)
8	Biodiversity Multi-scale Assessment (BioMAss)	LCA	Maier and Horn (2020)
9	Habitat Change Potential (HCP)	LCA	Damiani et al., 2021; Damiani et al., 2019)
10	Habitat conversion and fragmentation (HCF)	LCA	Kuipers et al. (2021)
11	Terrestrial biodiversity impacts of land inundation (LI)	LCA	Dorber et al. (2020)
12	Land use intensity specific biodiversity footprint (LUIS)[2]	LCA	Chaudhary and Brooks (2018)
13	Global Extinction Probability (GEP)	LCA	Verones et al. (2022)
14	Water temperature impacts on fish (WT)	LCA	Li et al. (2022)
15	Water consumption impacts on fish species richness (FSR)	LCA	Pierrat et al. (2023)
16	Forest Fragmentation Potential (FFP)	LCA	Larrey-Lassalle et al. (2018)
17	Entanglement impact on marine species of macroplastic debris (EI)	LCA	Woods et al. (2019)
18	Land Use Change Improved LCA method (LUCI-LCA)	Beyond-LCA	Chaplin-Kramer et al. (2017)
19	Product Biodiversity Footprint (PBF)	Beyond-LCA	Asselin et al. (2020)
20	Environmental Profit & Loss (EP&L)	Beyond_LCA	Kering (2017)
21	Global Biodiversity Score (GBS)	Beyond-LCA	CDC Biodiversite (2020)
22	Biodiversity Footprint Method (BFM)[3]	Beyond-LCA	Van Rooij et al. (2016)
23	Biodiversity Impact Metric (BIM)	Beyond-LCA	CISL (2020)

[1] Operational LCIA method included in Crenna et al. (2020).
[2] An advanced version of the model (Chaudhary et al., 2015) which is the interim recommendation for biodiversity impact assessment in LCA of the UN life cycle initiative (UNEP, 2016).
[3] Simplified operational webtool based on BFM is also available, which does not include all pressures from the method. In this paper the analysis is done according to full method.

- Six beyond-LCA, which follow life cycle thinking or ecosystem service accounting approaches, but does not necessarily use LCIA models in impact assessment phase and/or can be complemented with other approaches beyond LCA (#18–23).

3.2. Detailed analysis

In this section, the analysis of the selected methods regarding their goal and scope (section 3.2.1), data (section 3.2.2), and impact assessment (section 3.2.3) is presented.

3.2.1. Goal and scope

The aim of the methods is to assess the impact on biodiversity of human activities. Some methods are focused on a specific sector (e.g. *#11 LI* is applicable only to sectors converting terrestrial land to aquatic area, e.g. hydro power and aquaculture) whilst others on specific pressures regardless of the sector (e.g. land use, *#6 BV*), or on specific ecosystems (e.g. freshwater, *#14 WT*). Some methods aim at comparing alternative products (*#19 PBF*), at identifying impacts of possible options in future *(#22 BFM*), or at unveiling hotspots in terms of potential to affect areas at high biodiversity along the supply chain *(#23 BIM*).

Regarding the system boundaries, the goal of value chain impact assessment should be the compilation and evaluation of the inputs, outputs, and the associated potential environmental impacts of a product system across the whole life cycle, thus including all life cycle stages from cradle to grave. Out of the assessed methods, only one clearly states to include the entire life cycle (*#17 EI*), while four consider the impact on biodiversity from raw material production to the manufactured product exiting the company gate, similarly to a cradle-to-gate approach in LCA, excluding the use phase or end-of-life activities. *#18 LUCI-LCA* and *#23 BIM* consider only raw material sourcing. 17 methods do not provide specifications on the system boundary since it can be different depending on the application.

The reference state is expressed differently in the different methods using different wording (e.g. naturalness, potential natural vegetation, pristine undisturbed state) and it reflects the state of natural ecosystem before human perturbation (undisturbed), or before additional human perturbation (i.e. semi-natural), such as in *#18 LUCI-LCA*, where the reference state is set as the (assumed) current agricultural land extension, which is also the baseline in the method (year 2007). In methods including multiple impact assessment models, the reference state may have different definitions and may be set differently, leading to lack of overall consistency (Woods et al., 2018). For instance, in *#1 ReCiPe*, for land use the reference state is the potential natural vegetation. On the other hand, water use characterization factors are based on species presence in relation to river mouth discharge in 2005 (Xenopoulos et al., 2005). These differences in the reference state when analysing biodiversity impacts using different models together, should be interpreted and communicated transparently. Four methods do not specify reference state.

In the LCA framework, there are different approaches to the reference state definition. According to Vrasdonk et al. (2019), in the first applications of LCA to biodiversity assessment the reference situation, against which the impacts are assessed, is the absence of the studied production system, i.e. a human-free situation. However, several LCA authors have identified re-naturalisation as the most suitable reference situation, because land occupation postpones natural regeneration (Vrasdonk et al., 2019). The methods analysed in this study are in line with the first approach for the reference state, when the reference state is specified.

Regarding the baseline, it is set differently in the different methods. Methods *#6 BV, #9 HCP* and *#23 BIM* set the baseline as the present situation; *#18 LUCI-LCA* and *#20 EP&L* have selected a specific year as a baseline, 2007 and 2015, respectively; *#19 PBF* defines baseline as a 'standard' product, and for *#22 BFM*, the baseline is the situation before the company's activities. Method *#21 GBS* allows the user to define the baseline, i.e. the choice of baseline is independent from the assessment method. 14 methods do not specify which should be the baseline. This is because it can be adapted to the specific context and is usually represented by the situation at the time of the impact assessment.

To the authors' knowledge, seven out of 23 methods have been suggested in current initiatives and frameworks for Natural Capital Accounting on business and value chain. More details on goal and scope of the analysed methods can be find in Table 2 in the supplementary material.

3.2.2. Data

Data sources include literature data (e.g. economic value of ecosystem services), databases (e.g. LEDA Traitbase – Kleyer et al., 2008; PREDICTS – Hudson et al., 2017; WorldClim – Fick and Hijmans, 2017; GLOBIO – PBL, 2016), maps (e.g. GLOBIO 2015 land use map) and ecological surveys. Literature data is used for different purposes in the methods, e.g. in *#6 BV* literature data is used to calculate ecoregion factors (EFs) including the area share of grassland and forest, the area share of wetlands, the global extinction probabilities and the share of roadless areas so that the EFs reflect naturalness in different ecoregions worldwide, and in *#20 EP&L* to assess monetary value of impacts.

Regarding the data required for the application of the method, the use of primary data is always recommended. Primary data includes mainly company-specific data, e.g. on greenhouse gas (GHG) emissions, and other pollutant emissions (e.g. nutrients to water), land occupation, amount of raw materials used in the manufacturing process (at product level or at company level). In some cases, detailed data on land use is needed, e.g. location and land use management practices (*#6 BV, #7 FPD, #8 BioMAss, #7 LUIS, #23 BIM*). Secondary data, e.g. statistics, literature and input-output databases, like EXIOBASE, can also be used to complement primary data, if the latter is not available. More details on data sources of the analysed methods, and data required for the application of the methods, can be find in Table 3 in the supplementary material.

3.2.3. Impact assessment

Among the identified pressures, land use plays a prominent role since it is included in 19 methods (Table 4) being the only pressure considered in eleven approaches (*#5, EcoS, #6 BV, #7 FDP, #8 BioMAss, #10 HCF, #11 LI, #12 LUIS, #16 FFP, #18 LUCI-LCA, #205 EP&L, #23 BIM*). Methods *#9 HCP* and *#15 FSR* include only water use pressure, while *#14 WT* include only GHG emissions. Operational LCIA methods from *#1 ReCiPe* to *#3 IW+*, as well as *#13 GEP*, *#19 PBF* and *#21 GBS* include the biggest amount of pressures (6–7) considered in LCA. The latter two account also for pressures currently not captured in operational LCIA methods. Method *#19 PBF* includes 'invasive species' and 'species management', this last one encompassing 'overexploitation' aspects, such as hunting, poaching or overfishing but also including positive actions (e.g. installation of pollinators, use of various breeds, follow up of endangered species). Method *#21 GBS* includes fragmentation of natural ecosystems due to infrastructure, i.e. roads, and human encroachment, which quantifies bird and mammal abundance in relation to hunting pressure in the proximity of settlements. Method *#17 EI* include only pressure from waste in marine environment.

To assess the impacts caused by environmental pressures, the approaches use different impact assessment models (Table 4 in supplementary material). Operational methods *(#1 ReCiPe* to *#5 EcoS*) and LCA-based methods (*#6 BV* to *#17 EI*) gather different models to cover a specific cause-effect pathway of each impact category. Beyond-LCA approaches usually couple LCA methods and models with other elements, e.g. pressures currently not captured in operational LCIA methods (e.g. invasive species and overexploitation in *#19 PBF*). Beyond-LCA approaches like *#21 GBS* and *#22 BFM* use the GLOBIO model. GLOBIO covers both terrestrial (PBL, 2016) and freshwater ecosystems (GLOBIO-aquatic; Janse et al., 2015).

Seven out of 23 methods use biodiversity impact metrics taking into account the species populations EBV class, which includes species distribution and abundance in modelling or as a biodiversity metric. *#18 LUCI-LCA, #21 GBS,* and *#22 BFM* express impact in mean species abundance (MSA), which measures the mean abundance of individuals belonging to species in a disturbed situation, relative to their abundance in undisturbed setting. All approaches assessing the potentially disappeared fraction of species (PDF) fall in the community composition class, considering essentially taxonomic diversity (or proxies). MSA and PDF can be expressed per area (m^2, km^2, ha) in case of terrestrial impacts, or per volume (m^3) in case of aquatic impacts (freshwater or marine), or according to a unit of emitted substance.

Five methods use biodiversity impact metrics that are not directly related to an EBV class because they do not measure biodiversity per se. For instance, the Biodiversity Value Increment (BVI) used in *#6 BV* assess the level of hemeroby associated to different intensities of land use. Hemeroby is a concept that reflects the degree of human influence on a natural environment. Therefore, less hemeroby is one of the most important prerequisites for the conservation of global biodiversity. This approach is based on the evidence that there is a correlation between the decline in biodiversity and the decreasing number of habitat niches. *#9 HCP* measures freshwater habitat change potential based on habitat suitability for target fish species and invertebrates. The index used in *#16 FFP* represents the forest fragmentation based on metapopulation capacity; the scores used in *#19 PBF* for pressures of invasive species and overexploitation are proxies of biodiversity impact; the method *#20 EP&L* measures the economic value of biodiversity impact, and *#23 BIM*

Table 4
Pressures included in the methods.

#	Method	Land use	Water use	GHG emissions	Toxic emissions	Acidifying emissions	Other air emissions	Nutrient emissions	Invasive species	Overexploitation	Other pressures
1	ReCiPe	x	x	x	x	x	x	x	–	–	–
2	LC-Impact	x	x	x	x	x	x	x	–	–	–
3	IW+	x	x	x	x	x	x	x	–	–	–
4	SWise	x	–	x	x	x	x	x	–	–	–
5	EcoS	x	–	–	–	–	–	–	–	–	–
6	BV	x	–	–	–	–	–	–	–	–	–
7	FPD	x	–	–	–	–	–	–	–	–	–
8	BioMAss	x	–	–	–	–	–	–	–	–	–
9	HCP	–	x	–	–	–	–	–	–	–	–
10	HCF	x	–	–	–	–	–	–	–	–	–
11	LI	x	–	–	–	–	–	–	–	–	–
12	LUIS	x	–	–	–	–	–	–	–	–	–
13	GEP	x	x	x	x	x	x	x	–	–	–
14	WT	–	–	x	–	–	–	–	–	–	–
15	FSR	–	x	–	–	–	–	–	–	–	–
16	FFP	x	–	–	–	–	–	–	–	–	–
17	EI	–	–	–	–	–	–	–	–	–	Waste in marine environment
18	LUCI-LCA	x	–	–	–	–	–	–	–	–	–
19	PBF	x	x	x	x	x	x	x	x	x	–
20	EP&L	x	–	–	–	–	–	–	–	–	–
21	GBS	x	x	x	x	–	x	x	–	–	River dams, infrastructures, hunting
22	BFM	x	x	x	–	–	–	x	–	–	–
23	BIM	x	–	–	–	–	–	–	-	–	–

measures the amount of potential high biodiversity area used for raw material sourcing. However, the metrics of *#6 BV, #8 BioMAss*, and *#9 HCP* are calculated using biodiversity parameters that can be related to EBVs.

Only five of the methods considered in our study cover impact on marine, freshwater, and terrestrial ecosystems *(#1 ReCiPe, #2 LC-Impact, #3 IW+, #13 GEP, #19 PBF*), although resulting from different pressures. Toxicity impact on all three ecosystem types is modelled in *#1 ReCiPe, #2 LC-Impact, #3 IW+, #19 PBF* although in *#3 IW+* for terrestrial and marine ecotoxicity interim indicators are provided. Regarding acidification, *#3 IW+* includes terrestrial and freshwater acidification, while *#1 ReCiPe, #2 LC-Impact*, and *#19 PBF* include only terrestrial. The same applies also to eutrophication where *#1 ReCiPe* considers all three ecosystem types and the other three methods do not model terrestrial ecosystems. Three approaches cover only terrestrial and freshwater ecosystems *(#4 SWise, #21 GBS, #22 BFM*), three covers only freshwater ecosystems (*#9 HCP, #14 WT, #15 FSR*), and one only marine ecosystem (*#17 EI*). The remaining ones consider solely terrestrial ecosystems.

Method *#17 EI* includes an impact not currently covered in LCA: the entanglement impact on marine species due to macroplastic debris. This impact is assessed through potentially affected fraction of species (PAF). Also *#19 PBF* includes impacts not currently covered in LCA, namely 'invasive species' and 'species management', this last one encompassing 'overexploitation' aspects, such as hunting, poaching or overfishing but also including positive actions (e.g. installation of pollinators, use of various breeds, follow up of endangered species). These are assessed giving a score for several sub-indicators, e.g. potential production of invasive species or potential diffusion of invasive species, using qualitative evaluation. The final indicator is the average score across all sub-indicators.

Almost all approaches analysed include land use impacts (19 methods). The land use classes considered vary between methods (Table 5 in supplementary material). Methods *#18 LUCI-LCA, #21 GBS* and *#22 BFM* use GLOBIO 3.5 which considers eight different land use classes with different intensity levels for cropland (extensive, intensive, irrigated), pasture (from moderate to intensive, man-made), grassland (natural) and forest (natural, plantation, clear-cut harvesting, selective and reduced impact logging, burnt), having 16 different combinations in total. *#10 HCF* include eight land use classes, without different intensity levels. Methods *#8 BioMAss* and *#19 PBF* take into account six land use classes, but only *#8 BioMAss* includes different intensity levels. Also *#7 FPD* includes six land use classes, although three of them are used as baselines. Methods *#11 LI* and *#12 LUIS* includes five land use classes, but only *#12 LUIS* includes different intensity levels. Methods *#6 BV* and *#23 BIM* take into account four different classes (e.g. forest, pasture, arable, urban) with different intensity levels (e.g. minimal, light, intense). Method *#16 FFP* includes only one land use class (forest) with 8 sub-classes. Methods *#13 GEP* and *#20 EP&L* do not specify land use classes.

Species groups considered vary between methods and impact categories (Table 6 in supplementary material). While some of the species groups described in the reference methods could be easily linked to taxonomic groups, such as mammals, birds or amphibians, some others correspond more to functional species groups, such as macroinvertebrates, zooplankton or algae, and could therefore not be unambiguously attributed to taxonomic groups. The rest of this section therefore describes species groups that can be either taxonomic or functional groups to be as descriptive as possible, while our evaluation (section 3.2.4) only considers taxonomic groups to make methods as comparable as possible.

Land use impacts on biodiversity are assessed taking into account from one (plants in *#4 SWise* and *#7 FPD)* to eight species groups (arthropods, other invertebrates, birds, amphibians, reptiles, mammals, vascular plants and moss for *#1 ReCiPe, #3 IW+* and *#5 EcoS*) while three methods (*#6 BV, #8 BioMAss* and *#20 EP&L*) do not specify or do not take into account any group in particular. Methods taking into account climate change impacts on biodiversity consider from one (freshwater fishes for *#14 WT*) to six species groups (mammals, birds, amphibians, reptiles, arthropods, and vascular plants for *#21 GBS* and *#22 BFM*). For water use impacts, methods *#2 LC-Impact and #19 PBF* consider the loss of wetland habitat and water stress due to water consumption, and the consequence on five taxonomic groups (birds, mammals, reptiles, amphibians, and vascular plants), while *#9 HCP* quantifies potential habitat change due to water consumption and river discharge alteration, based on habitat suitability for target bony fish, and macroinvertebrates, and *#15 FSR* takes into account only freshwater fishes. Methods *#21 GBS* and *#22 BFM* are based on the GLOBIO aquatic model (Janse et al., 2015), which aggregates impacts in different freshwater habitats taking into account different species groups: two (macroinvertebrates and fishes) in lotic ecosystems, five (macroinvertebrates, fishes, algae, macrophytes, zooplankton) in lentic ecosystems, and seven (plants, mosses, fishes, amphibians, macroinvertebrates, birds, mammals) in wetlands.

Method *#21 GBS* proposes a method to integrate ecotoxicity impacts from ReCiPe 2016, which includes terrestrial ecotoxicity characterization factors for 18,593 substances and freshwater ecotoxicity for 30,991 substances, with GLOBIO mean species abundance indicators (also terrestrial and aquatic species densities used in the impact assessment are from ReCiPe 2016). Method *#2 LC-Impact, #3 IW+*, and *#19 PBF*, include ecotoxicity calculated by the USEtox model from species sensitivity distributions of algae, crustaceans, fish, molluscs and nematoda. They also include terrestrial acidification assessed on vascular plants (*#3 IW+* quantifies also marine and freshwater acidification). In addition, *#2 LC-Impact* and *#19 PBF* include photochemical ozone formation impact on plants. More details on aspects related to impact assessment of analysed methods is available in the supplementary material.

3.2.4. Evaluation

The evaluation of the methods regarding how well biodiversity is considered as described in section 2.2. is presented in Fig. 2 (categories covered by each method for each criteria assessed). Overall, no method performs well on all criteria, but some methods perform better than others for specific criteria. Regarding the "pressures" criterion, the best performing method is *#19 PBF* as it covers the five main direct drivers of biodiversity loss. On the contrary, *#9 HCP* and *#15 FSR* perform badly in our evaluation because they cover only water use pressure, which is not among the five main direct drivers of biodiversity loss considered in our evaluation here. For the "ecosystems" criterion, five methods equally perform best as they cover terrestrial, freshwater and marine ecosystems: *#1 ReCiPe, #2 LC-Impact, #3 IW+, #13 GEP* and *#19 PBF*. Methods *#1–3* are already operational LCA-methods, *#13 GEP* is a recent LCA-based method proposal, and *#19 PBF* beyond-LCA method. Concerning the "taxonomic groups" criterion, the best performing method is *#3 IW+* with 15 taxonomic groups covered, closely followed by *#13 GEP* with 14 taxonomic groups covered, both being LCA-based methods. For the "EBV classes" criterion, the best performing method is *#9 HCP* as the metric it uses ("Habitat Change Potential") considers biodiversity parameters referring to four distinct EBV classes. Finally, regarding the fundamental biodiversity aspects to consider in LCA, while no method addresses both ecosystem multifunctionality and global species extinctions, four methods address ecosystem multifunctionality *(#7 FPD, #18 LUCI-LCA, #21 GBS* and *#22 BFM*), and four others address global species extinctions (*#10 HCF, #13 GEP, #14 WT* and *#15 FSR*).

This evaluation exercise also permits to highlight the commonalities and gaps in the methods. For instance, while most of the methods examined address the pressure due to land use in terrestrial ecosystems, only one method (*#19 PBF*) addresses the pressures due to overexploitation and invasive alien species, and aquatic ecosystems are less covered by the methods examined. The taxonomic groups most frequently included are mammals, birds, amphibians, reptiles, and

#	Method	Pressures					Ecosystems			Taxonomic groups																	Essential Biodiversity Variable Classes						Fundamental aspects	
		Land use	Overexploitation	Climate change	Pollution	Invasive species	Terrestrial	Marine	Freshwater	Mammals	Birds	Amphibians	Reptiles	Arthropods	Bony fishes	Cartilaginous fishes	Plants	Molluscs	Cnidarians	Annelids	Echinoderms	Chlorophyta	Rhodophyta	Heterokontophyta	Fungi	Others	Genetic composition	Species populations	Species traits	Community composition	Ecosystem function	Ecosystem structure	Global species extinctions	Ecosystem multifunctionality
1	ReCiPe 2016	x		x	x		x	x	x	x	x	x	x	x	x		x								x	x				x				
2	LC-Impact	x		x	x		x	x	x	x	x	x	x	x	x		x	x	x	x	x					x				x				
3	Impact World+	x		x	x		x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x		x				x				
4	StepWise	x		x	x		x		x								x									x				x				
5	EcoScarcity 2013	x					x			x	x	x	x	x			x									x				x				
6	BV	x					x																							x		x		
7	FPD	x					x										x											x	x	x				x
8	BioMAss	x					x																					x		x				
9	HCP								x						x											x		x	x	x		x		
10	HCF	x					x			x	x	x	x																	x			x	
11	LI	x					x			x	x	x	x																	x				
12	LUIS	x					x			x	x	x	x				x													x				
13	GEP	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x	x				x			x	
14	WT			x					x						x															x			x	
15	FSR								x						x															x			x	
16	FFP	x					x			x	x																							
17	EI				x			x		x	x		x		x	x														x				
18	LUCI-LCA	x					x			x	x	x	x	x			x											x						x
19	PBF	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x									x				x				
20	EP&L	x					x																											
21	GBS	x		x	x		x		x	x	x	x	x	x			x									x		x						x
22	BFM	x		x	x		x		x	x	x	x	x	x			x									x		x						x
23	BIM	x					x			x	x	x					x											x						

% covered	0	6	12	17	18	20	24	29	33	35	41	47	50	53	60	67	71	82	88	100

Fig. 2. Categories covered by the methods for each criterion assessed: pressures (aligned with the key direct drivers of biodiversity loss – Millenium Ecosystem Assessment, 2005), ecosystems, taxonomic groups, essential biodiversity variable classes, and fundamental biodiversity aspects to consider. The colours represent the percentage of categories by criterion that each methods covers, with a gradient going from red (corresponding to 0%) to dark green (corresponding to 100%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

plants. However, even the most complete methods in terms of taxonomic groups considered only include a small portion of the known and unknown biodiversity. For instance, some important marine taxa are completely overlooked (e.g. sponges). Thus, increasing biodiversity coverage in terms of taxonomic groups remains a crucial issue regarding the improvement of biodiversity assessment. The biodiversity metrics are mostly related to the EBV class "community composition", mainly due to the use of species richness indicators (e.g. PDF). The other EBV classes are less captured, and consequently essential biodiversity facets such as genetic composition, species traits, and ecosystem functioning are mostly overlooked in these methods.

It must be borne in mind in any case, that the evaluation of methods is carried out equally on models focusing on only one impact category and methods including several impact models. Therefore, models focusing on one impact category only necessarily perform less than those including several ones for the criterion "pressures". Moreover, the evaluation does not address the scientific robustness of the impact models, which must necessarily be considered in order to choose the most suitable method (e.g. the difference between the conversion from midpoint to endpoint indicators in ReCiPe or mechanistic endpoint models included in LC-Impact).

4. Conclusions

This review assesses approaches to biodiversity impact assessment, considering both LCA-based methods and models as well as other methods used to address impacts on biodiversity. The objective of this study was to i) analyse the progress in the development of methods for the assessment of biodiversity, ii) the level to which the methods are based on LCA or life cycle thinking, and iii) the extent to which complementarities exist between LCA and beyond-LCA approaches. As a result, 64 biodiversity assessment methods were identified, of which 23 methods were selected for a detailed analysis following the criteria presented in the materials and methods section, including five operational LCIA methods. All selected methods use life cycle thinking as an underpinning approach. 17 methods were purely LCA approaches and include underpinning LCIA models, while six methods were complemented with other approaches or models beyond the LCA domain.

Many methodological aspects were not always reported comprehensively by the methods and models documentation. For example, system boundary was reported only by six methods, and only one stated to include all stages from cradle to grave. Species groups covered by the methods were either reported as taxonomic groups or functional groups or a mix of both, which hinders a proper analyses of the methods regarding their taxonomic coverage. Many methods included in the detailed analysis use the same data sources for the reference state and impact assessment. The most commonly used data sources were GLOBIO and IUCN. In case of LCA-based methods, the most common metric was PDF (9 out of 17 methods), while for beyond-LCA methods the most common metric was MSA (3 out of 6). As PDF (when it is estimated a global scale) approximates potentially disappeared fraction of species in global level (i.e. species extinctions) and MSA approximates ecosystems multi-functionality (Marques et al., 2021), this illustrates very well how LCA-based methods and beyond-LCA methods are complementary in capturing the two fundamental biodiversity aspects to be covered in assessing impacts on biodiversity. If only one method needs to be chosen, then the choice of the best method must necessarily involve an evaluation of the discriminating power of the model and methods, an assessment of the scientific robustness thereof, and the type of indicators by which the result is to be communicated.

Our review highlights that currently, no method is able to capture well at the same time the variety of (i) pressures on biodiversity, (ii) ecosystems, (iii) taxonomic groups, (iv) EBVs classes. However, the analysis shows that some methods perform better than others for each of these five criteria. Research perspectives to overcome those gaps, and, eventually, select a method or develop a new one that would allow to capture well the different criteria mentioned above are related to i) increase the completeness of methods with regards to pressures and taxonomic groups covered, and ii) to enhance the descriptive power of the methods on the various components of biodiversity such as genetic diversity, community composition and structure, and ecosystem functionality. Further development of ecosystem quality assessment should, ideally, also include the evaluation of ecosystem services along value chains, integrating LCA and Natural Capital Assessment approaches.

CRediT authorship contribution statement

Mattia Damiani: Formal analysis, Methodology, Writing – original draft. **Taija Sinkko:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Carla Caldeira:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Davide Tosches:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Marine Robuchon:** Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Serenella Sala:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

"The authors declare no conflict of interest."

Data availability

all data used are within the paper

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Appendix A. Supplementary data

A supplementary material document is available including the complete list and short description of the methods and models identified, and details on goal and scope, data, impact assessment, land use assessment methods, as well as taxonomic/species groups coverage of the methods and models reviewed in detailed analysis. Supplementary data to this article can be found online at [https://doi.org/10.1016/j.eiar.2023.107134].

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