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Biodiversity assessment of value chains: state of the art and emerging challenges

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ABSTRACT

The consumption of materials and products is one of the drivers of biodiversity loss, which in turn affects ecosystem functioning and has worldwide socio-economic consequences worldwide.. Life cycle assessment (LCA) is a reference methodology for appraising the environmental impacts of products along their value chains. Currently, a generally accepted life cycle impact assessment (LCIA) framework for assessing biodiversity impacts is lacking. The existing LCIA models present weaknesses in terms of the impact drivers considered, geographical coverage, as well as the indicators and metrics adopted.

Sound ecological indicators and metrics need to be integrated in order to better assess the impacts of value chains on biodiversity, on a global, regional, and local scale.

This review analyses studies which, using a life cycle perspective, assess the impacts of products' and services' value chains on biodiversity. We identify and discuss promising synergies between the studies which look beyond the life cycle context, and apply other biodiversity metrics.

Our results highlight that the existing metrics of biodiversity impact assessment in LCA are poor at capturing the complexities of biodiversity. There are operational models at the midpoint level that expand on the assessed dimensions of biodiversity (e.g. ecosystem structure), and the drivers of biodiversity loss (e.g. assessment of species exploitation), but efforts are required to fully include these models in the LCA framework. In the business domain, many initiatives are developing frameworks to assess impacts on biodiversity. Many approaches make use of LCIA methods and input-output databases. However, these are generally coupled with other biodiversity metrics. This shows that the current LCA framework is not yet sufficient to support decision-making based on different sets of biodiversity indicators. Ecosystem accounting may provide important ecological information for both the inventory and the impact assessment stages of LCA, helping to disentangle the relationship between biodiversity and ecosystem services.

Looking beyond the LCA domain can lead us to new ways of advancing the coverage of biodiversity impacts, in a way that increases the relevance of LCA across a wider range of areas. Future work should assess the indicators provided in various policy contexts.

1. INTRODUCTION

Biodiversity is a multifaceted concept; the Convention of Biological Diversity (CBD) defined it as “the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes

diversity within species, between species and of ecosystems”¹. Biodiversity can be further defined as the “infrastructure” which supports the functioning of life on Earth², as it underpins the ecological processes that provide food security, climate regulation, and other important environmental functions relied on by human societies. Recent assessments on the status of biodiversity and ecosystems show a critical and worsening situation that puts human wellbeing at risk^{3, 4}. The World Wide Fund for Nature (WWF) Living Planet Index² has recently been used to indicate the global status of biodiversity, and depicts a critical situation. In fact, the index, which builds on data collected between 1970 and 2014, reports a 60% decline in the size of vertebrate populations on a global scale, with the major threats to species directly linked to human activities. This loss across the global is valued at around €50 billion per year⁵.

Biodiversity loss is not solely an environmental concern, as it also has important consequences on worldwide socio-economic systems⁶. Halting the rate of biodiversity loss is an international challenge, one which is promoted by the Convention on Biological Diversity’s (CBD) Aichi Biodiversity Targets⁷, and by the United Nations’ (UN) Sustainable Development Goals (SDGs) 14 (Life below water) and 15 (Life on land)⁸. Having scientifically robust metrics and indicators is essential for tackling biodiversity loss from a value chain perspective⁹, enabling the current company-driven loss of biodiversity to be monitored, as well as allowing for mitigation strategies for future impacts⁹ to be put in place. One possible way forward could be to integrate sound ecological metrics and indicators with government- and industry-related approaches; this could improve assessments of how biodiversity is impacted, and further our understanding of the direct and indirect drivers of biodiversity loss at a global, regional, and local level.

There is currently an emphasis on developing specific approaches to support the assessment of how value chains and businesses affect the environment. One such approach is the recent

“Aligning Biodiversity Measures for Business” project. This project brings together academic institutions, non-governmental organisations, and businesses. It aims to establish a common view on how to measure, monitor, and disclose businesses’ impacts on biodiversity, as well as the extent to which businesses depend on biodiversity. The project aims also to promote integrating more comprehensive indicators of corporate contribution to global biodiversity goals¹⁰.

In policy and industrial systems, Life Cycle Assessment (LCA) is becoming more and more prominent as a standardised method¹¹ for assessing the potential environmental impacts of value chains, and evaluating the entire life cycle of a product or service.

There are several weaknesses to the life cycle-based metrics and indicators which are currently used to quantify value chains’ impacts on biodiversity, and as of yet, there is no generally accepted approach^{6, 12}. Recent reviews on the integration of biodiversity into LCA have laid out several recommendations for moving the field forward^{13–16}. The most common recommendations are: (i) to incorporate more dimensions of biodiversity (which will probably require several indicators), (ii) to cover more drivers of biodiversity loss (habitat change through land use has been the most addressed driver), and (iii) to include spatial detail in biodiversity impact assessments. In fact, LCA integrates only a few aspects of biodiversity, usually identified at species level, such as extinction rate and species richness^{13, 14}. In contrast, the ecological literature explores metrics and indicators which measure biodiversity change, and cover all areas of biodiversity included in the CBD definition. Pereira et al. (2013)¹⁷ defined the Essential Biodiversity Variables (EBVs), inspired by the Essential Climate Variables (ECVs), which constitute a common framework to monitor biodiversity change worldwide. The EBVs include the following six general categories of biodiversity metrics: genetic composition, species populations, species traits, community composition, ecosystem structure, and ecosystem function.

Building on previous reviews on the topic^{13, 14, 18}, the aim of this paper is to help design a better LCA framework by highlighting its current weaknesses with respect to how impacts on biodiversity are quantified, and by drawing suggestions for future improvement. LCA is taken as "starting point" due to its systematic approach to address resource use and emissions along the value chains, its comprehensiveness in covering multiple environmental dimensions, and the international efforts seeking harmonization and consensus from data quality to models for impact assessment. This work specifically, presents and discusses possible links and convergences between LCA and other existing frameworks developed both within and beyond life cycle thinking, with the aim of possibly linking these frameworks with products and associated value chains. Our intention is for this paper to support both environmental policy (in which LCA is becoming a relevant tool, that is listed in the Better Regulation Toolbox of the European Commission), and better choices in the industrial system.

2. MATERIALS AND METHODS

Firstly, we conducted a literature review, from which we identified the current methods and associated indicators and metrics which are applied in the existing LCA framework. Secondly, we reviewed the literature on other approaches and the indicators already in use to support biodiversity assessment along value chains. Throughout this paper, we will highlight major knowledge gaps in the way that current LCIA models quantify impacts on biodiversity, and we will identify promising synergies between LCA and other approaches for the future improvement of LCA frameworks.

We will structure our work in two macro areas, one covering indicators, models, and methods within the existing LCIA framework, and the other covering indicators, models, and methods

“Beyond LCIA” (Figure 1). In the former macro area, we make a distinction between operational and non-operational models and methods. “Operational models and methods” include all ‘endpoint’ models and methods available in LCA software, and those that are widely used by LCA practitioners. “Non-operational models and methods” can be subcategorised into “non-operational midpoint models and methods” and “non-operational endpoint models and methods”. In LCA, ‘midpoint’ and ‘endpoint’ refer to where in the environmental cause-effect chain the environmental consequences are assessed. ‘Midpoint’ models and methods assess environmental consequences earlier in the cause-effect chain, typically linking the use of natural resources or generation of emissions to an impact on the environment (e.g. climate change, land use, ecotoxicity). Impact is derived using a simple multiplication between the mass of resource use or emissions generated, and specific factors called characterisation factors (CFs); impact categories (ICs) are then used to represent these impacts. ‘Endpoint’ models and methods link the midpoint environmental impact to damages to areas which are important to society (areas of protection, AoP). Typically, in LCA, these AoPs are human-health, natural resources, and ecosystem quality. Biodiversity loss, quantified in terms of species loss, is used as the metric to assess damages to ecosystem quality. A list of LCA-related terms and their definitions is provided in the Supporting Information (SI; Table S1).

In the “Beyond LCA” macro area, we identified two main categories. Firstly, “other life cycle thinking approaches” refers to other methods that can be used to quantify environmental impacts from a life cycle perspective (e.g. those used in input-output approaches). These approaches make use of methods such as multi-regional input-output (MRIO) tables and biophysical accounting, and differ from “within LCA” approaches since their underpinning method for building inventory is different from the standard process-based LCA framework. Nevertheless, as shown in the

Results Section, some of these approaches make use of specific elements of LCA, such as LCIA methods. Secondly, “ecosystem services (ES) accounting approaches” intend to show approaches developed in a more applied context.

Additionally, “business-applied approaches” lies in between the two aforementioned macro areas, since some studies use both LCA and beyond LCA approaches, modified or complemented for specific business objectives. We chose to discuss this category under the "beyond LCA" macro area for the sake of simplicity.

Figure 1. Classification of the approaches selected, concerning biodiversity impact assessment; LCIA = life cycle impact assessment, ES = ecosystem services. The dashed lines in the “beyond LCIA” macro area indicate proximity to the LCA method (smaller dashes = more proximate to LCIA), and a decreasing ease of integration of the approaches and metrics into the life cycle assessment framework. The arrows from Areas 1 and 3 to Area 4 indicate businesses’ approaches which use methods and indicators that come from these two areas, but that can be changed or complemented to meet specific objectives.

Previous reviews on the inclusion of biodiversity and ecosystem services into LCA^{13, 14, 18, 19}, and approaches developed by business for quantifying biodiversity impacts¹², represent the starting point of the present work.

For every category except “ES accounting approaches”, we reviewed the literature according to four main criteria: (i) the impact drivers covered by each approach, and their link with LCA impact categories, (ii) the metric and related units used to reflect impacts on biodiversity, (ii) the spatial resolution of the method, and (iv) the relationship between the metric and EBVs categories¹⁷. The EBVs are being developed by the Group on Earth Observations’ Biodiversity Observation Network (GEO BON) to build a framework for monitoring worldwide biodiversity change. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) proposes EBVs as an appropriate framework for determining common metrics for biodiversity modelling, reporting, and observation communities^{20, 21}. Also, the CBD supports the work of GEO BON in further developing the EBVs (CBD/SBSTTA/21/INF/1).

3. RESULTS

3.1 Within LCA

3.1.1. Operational models and methods

Operational models and methods refer to the endpoint models and methods available in LCA software, and which are widely used by LCA practitioners. Endpoint methods are based on either ‘damage-oriented’ modelling or ‘distance-to-target’ approaches. Concerning biodiversity impacts, damage modelling typically quantifies the number of species that potentially disappear from a

region (country, continent, and world) due to human-induced changes in environmental states (e.g. after emissions of nutrients, climate-altering, or toxic substances). Distance-to-target approaches use environmental target levels, established from policy or with an ecological meaning (the carrying capacity of ecosystems), and derive weights based on the distance to the target: the more distant to the target, the more important the impact becomes^{22, 23}. Table 1 shows the current LCA endpoint methods which address the potential impacts on biodiversity.

Table 1. LCIA endpoint methods which are currently operational for biodiversity impact assessment.

LCIA method	Impact categories for biodiversity*	Metric/Indicator of impact	Spatial resolution of impact assessment	Relation to categories of EBVs	Reference
ReCiPe 2016	<ul style="list-style-type: none">• Climate change (terrestrial and freshwater ecosystems)• Photochemical ozone formation• Terrestrial acidification• Freshwater eutrophication• Freshwater, marine, and terrestrial ecotoxicity• Land use• Water use (terrestrial and freshwater ecosystems)	Potentially disappeared fraction (PDF) of species over time (years)	Country, global	Community composition	Goedkoop et al. (2009) ²⁴ (superseded ⁸), Huijbregts et al. (2016) ²⁵
LC Impact	<ul style="list-style-type: none">• Climate change (terrestrial and freshwater ecosystems)• Photochemical ozone formation• Terrestrial acidification• Freshwater and marine eutrophication• Freshwater, marine, and terrestrial ecotoxicity• Land stress• Water stress	PDF of species over time (year)	Country, ecoregion, global ^a	Community composition	Verones et al. (2016, submitted) ^{26, 27}
Impact World+	<ul style="list-style-type: none">• Climate change (ecosystem quality)• Freshwater and terrestrial acidification• Freshwater and marine eutrophication	PDF of species over time (year)	Country, ecoregion, global	Community composition	Bulle et al. (2019) ²⁸

LCIA method	Impact categories for biodiversity*	Metric/Indicator of impact	Spatial resolution of impact assessment	Relation to categories of EBVs	Reference
	<ul style="list-style-type: none"> Land transformation and occupation for biodiversity Water availability Freshwater ecotoxicity <p><i>Interim:</i></p> <ul style="list-style-type: none"> Photochemical ozone formation Terrestrial and marine ecotoxicity Ionising radiations 				
Stepwise	<ul style="list-style-type: none"> Global warming (fossil/non-fossil) Photochemical ozone – vegetation Terrestrial acidification Terrestrial and aquatic eutrophication Terrestrial and aquatic ecotoxicity Nature occupation 	Biodiversity Adjusted Hectare Year (BAHY) ^b	Global	Community composition	Weidema et al. (2008) ²⁹ , Weidema (2009) ³⁰
EcoScarcity 2013	<ul style="list-style-type: none"> Biodiversity damage potential through land use 	Eco-points (UBP)	Country, global ^c	Community composition	Frischknecht et al. (2006) ³¹ (superseded), Frischknecht & Büsser-Knöpfel (2014) ³²

* Details are available in Table S2 in the SI.

§ "Superseded" means that the method has been either complemented (e.g. with additional impact categories) or replaced by a more recent one.

^a Native resolution of midpoint indicators are also available at finer resolutions, up to 0.05x0.05°

^b 1 BAHY corresponds to - 10,000 PDF m² years

^c EcoScarcity method was initially developed on Swiss national goals; however, it can be adapted to be used according to other countries' targets (see ²²)

With the exception of Eco Scarcity 2013³², all endpoint methods analysed (see Table 1) are damage-oriented methods, covering between 8 and 11 impact categories converging in the AoP "ecosystem quality". The impact pathway for marine acidification is available only in Impact World+²⁸.

Impacts are mainly quantified in time-integrated species disappearance, as PDF years (on different spatial scales), which is the most commonly used metric in LCA for biodiversity. One damage-oriented method, Stepwise^{29, 30}, quantifies impacts on biodiversity in terms of biodiversity-adjusted hectare-years. Unlike the other methods analysed, Eco Scarcity 2013³² is a distance-to-target method, and covers only one impact category, land use, meaning that it is limited to the impact of land occupation. However, it is the only method so far which accounts for land management intensity.

Taxa coverage depends on the modelling behind each impact category; for instance, for climate change, vascular plants, butterflies, and fish species are representative taxa in ReCiPe²⁵, while vascular plants together with mammals, birds, reptiles, amphibians, and butterflies are used in LC impact^{26, 27}. Species' vulnerabilities are only integrated in LC impact^{26, 27} metrics, and this is based on information from the International Union for Conservation of Nature (IUCN), which allows for local to global species loss to be calculated..

The regionalization of impacts is allowed to varying extents for the majority of methods. With regards to the dimensions of biodiversity covered, endpoint methods thus focus on one of the eight EBV classes, community composition. An in-depth analysis of each method is presented in the SI.

3.1.2. Non-operational models and methods

There are some LCIA applicable models, both at endpoint and midpoint level, which address impacts on biodiversity-related features that are currently missing in the LCA framework. However, not all of these models are operational, as some of them have not been tested in case studies, or have only been applied for the impact assessment of a few substances.

3.1.2.1. Non-operational midpoint models and methods

Midpoint modelling may cover impacts on biodiversity features. These models mainly focus on two of the major impact drivers for biodiversity³³, namely resource overexploitation (e.g. Emanuelsson et al., 2014³⁷; Hélias et al., 2018³⁴), and habitat alteration (e.g. Geyer et al, 2010³⁵; De Souza et al., 2016³⁶). It should be noted that natural biotic resources have a twofold role: they are at the same time both natural resources and components of the ecosystem³⁷. As a result, their exploitation may generate impacts on both AoPs “natural resources” and “ecosystem quality”, according to the selected impact pathways.

The studies that we analysed span from more comprehensive frameworks³⁸ to detailed indicators of impacts³⁴ (Table 2). They provide either preliminary or operational characterisation factors, built on ecologically-related concepts and metrics (e.g. renewability and maximum sustainable yield; MSY), at different spatial scales.

Table 2. Most recent advancement in LCA midpoint models, focusing on aspects related to biodiversity.

Impact category	Metric/Indicator	Spatial coverage	Relation to categories of EBVs	Reference
Biotic resource use	Year	Global	Ecosystem function	Crenna et al. (2018) ³⁸
Lost potential yield - LPY	kg _{LPY} year ⁻¹	Stock, fishing region, global	Species populations	Emanuelsson et al. (2014) ³⁹
Biotic resource use	Year	Stock, fishing region, global	Ecosystem function	Langlois et al. (2014) ⁴⁰
Biotic resource use	Year	Stock, fishing region, global	Species populations	Hélias et al. (2018) ³⁴
Sea use	kg C eq.	Biomes and marine provinces	Species populations	Langlois et al. (2015) ⁴¹
Land use	Hemeroby-based biodiversity impact potential	Local	Ecosystem structure	Geyer et al. (2010) ³⁵
Land use	Functional Diversity Index	Ecoregion	Species traits	de Souza et al. (2016) ³⁶

Further developments have been sector-specific, for example, models for quantifying impacts on biodiversity from renewable energy technologies such as hydropower and windfarms^{42, 43}, covering both existing and new impact pathways.

Additionally, Winter et al. (2018)⁴⁴ proposed a methodological framework that aims to cover all drivers of biodiversity loss on a global scale, at midpoint level. The novelty of this framework lies in that it covers impacts on all levels of biodiversity, namely genetics, species, and ecosystem. It combines areas of the ecological domain, such as the vulnerability-based indicators from WWF, with expert judgement, and life cycle thinking background information. Nevertheless, this framework is not yet fully operational, as no complete case study is available for all categories.

The dimensions of biodiversity covered increases in this case, covering four EBVs. A detailed analysis of each study is included in the SI.

3.1.2.2. Non-operational endpoint models and methods

‘Single-endpoint’ modelling refers to the endpoint damage-oriented modelling of a single impact driver. Over the years, research has improved, particularly in the modelling of land use-related impacts. Guidelines for harmonising modelling efforts were drawn under the flag of the UNEP/SETAC Life Cycle Initiative¹³, and the limitations of diverse land use models have been identified⁶. One limitation is the need to regionalise the impacts of land use, considering different land use management and their intensity, as well as the global fragmented distribution of biodiversity, and its vulnerability.

Table 3. Most recent advancement in LCA endpoint models, focusing on aspects related to biodiversity.

Impact category	Metric/Indicator of impact*	Spatial resolution of impact assessment	Relation to categories of EBVs	Reference
Land use	PDF year m ⁻² (occupation); PDF m ⁻² (transformation)	Country, ecoregion, global	Community composition	Chaudhary & Brooks (2018) ⁴⁵
Land use	PDF year m ⁻² (occupation); PDF m ⁻² (transformation)	Ecoregion	Community composition	Larrey-Lassalle et al., (2018) ⁴⁶
Land use	Species richness and habitat frequency biodiversity impact potential Species richness and habitat evenness biodiversity impact potential	Local	Species populations; Community composition	Geyer et al. (2010) ³⁵
Invasive species	PDF·m ³ ·year	Local (river scale)	Community composition	Hanafiah et al. (2013) ⁴⁷
Entanglement in macroplastic waste	PAF.g.km ⁻²	0.1° x 0.1°	Community composition	Woods et al. (2019) ⁴⁸

* PDF = potentially disappeared fraction of species; PAF = potentially affected fraction of species

In an attempt to overcome existing weaknesses, recent methods have embraced more details in the modelling of land management intensity⁴⁵, and in the inclusion of habitat fragmentation⁴⁶ (Table 3). A review by Kuipers et al. (2019)⁴⁹ identified the limited data input from life cycle inventories, the lack of species data concerning their affinity to different land use types, species' dispersal characteristics, and response to habitat structure (edges effects and isolation), as the main challenges to including habitat fragmentation in LCIA. Impacts are assessed on a species richness basis at different spatial scales, from a local⁴⁷ (making the method not applicable in large-scale supply chains) to a global level.

Community composition and species populations are the EBVs classes covered by single endpoint studies. A detailed analysis of each study is included in the SI.

3.2. Beyond LCIA

3.2.1. Other life cycle based approaches

MRIO analysis and biophysical accounting methodologies have been used to quantify the pressures and impacts on biodiversity through a life cycle perspective (Table 4). These methods are typically applied at sectoral level (e.g. agriculture) or the level of product groups (e.g. apples), and one of their main features is that they cover international trade relations, allowing them to trace the impacts, from production activities to final consumption activities.

A direct connection with LCA impact categories can be found in the majority of these methods, since they link biodiversity losses to land use practices, and greenhouse gas emissions contributing to climate change. The only method that does not allow for a direct link with LCA is the one adopted by Lenzen et al. (2012)⁵⁰. On the other hand, this method covers a broader range of drivers of impact, many of them not included in the existing LCIA framework (e.g. residential development, aquaculture, invasive and other problematic species).

Biodiversity loss is generally quantified in terms of mean species abundance (MSA), or species extinction. MSA measures the mean abundance of original species in a disturbed situation, relative to their abundance in undisturbed ecosystems, providing an indication of the degree to which an ecosystem is intact⁵¹. This metric reflects the EBVs categories covered by the methods. Indeed, the dimensions of biodiversity covered are mainly relating to species population and community composition.

Biophysical and MRIO databases have also been used to analyse the impacts on biodiversity from the consumption activities of specific countries^{e.g.52, 53}. The metrics used in these studies are reflected in Table 4.

Table 4. The most recent advancements in biodiversity assessments conducted in the context of other life cycle-based approaches.

Relationship with LCA impact category	Metric/Indicator	Spatial coverage	Relation to categories of EBVs	Reference
Not direct	Species threats	Country	No	Lenzen et al. (2012) ⁵⁰
Land use Climate change	Mean species abundance (MSA)	Country	Species populations	Wilting et al. (2017) ⁵⁴
Land use (via human appropriation of net primary productivity)	Occupied bird ranges and missing individual birds	Country	Species populations	Kitzes et al. (2017) ⁵⁵
Land use Climate change	Bird species extinctions Carbon sequestration potential lost	Country	Community composition	Marques et al. (2019) ⁵⁶
Land use	MSA loss Relative abundance loss Relative within-sample species richness loss Vulnerability-weighted global relative species loss	Country	Community composition	Marquardt et al. (2019) ⁵⁷

3.2.2. Business-applied approaches

Companies, on the course of their business, have impacts on biodiversity, as they use natural resources, emit potentially harmful substances into the environment, occupy and manage lands,

and so on. Currently, companies are showing a lot of interest in quantifying their impacts on biodiversity in a simple, practical, and meaningful way, communicating their efforts towards biodiversity preservation, and driving decision-making by investors. LCA is the suitable method of choice when a company is interested in assessing impacts throughout its whole value chain. However, companies are also developing other approaches to assess their biodiversity impacts. Some companies couple biodiversity metrics, other than the PDFs, with life cycle based methods (like LCA and input-output), whilst others develop completely different approaches. Lammerant et al. (2018)¹² provide a comprehensive review of the main approaches developed and adopted by businesses to date within and beyond the LCA domain.

Some of these approaches use LCIA and complementary methods (Table 5), either using an input-output database paired with LCIA characterisation factors, or a LCA process-based database, coupled with different impact assessment models, or by means of qualitative information as a supporting tool. For instance, the Biodiversity Footprint Approach⁵⁸ uses an input-output database for information on environmental pressures, and the LCIA ReCiPe method to quantify the impacts on biodiversity. At the same time, the Global Biodiversity Score⁵⁹ uses inputs from LCA and input-output databases to model the impacts on biodiversity, by means of the Global Biodiversity (GLOBIO) impact assessment model⁵¹. Finally, the Product Biodiversity Footprint⁶⁰ makes use of the LC-Impact method, complementing it with qualitative information on invasive species and species management¹².

Some of the approaches, which are not directly related to LCIA, make explicit the link between the production processes of a company and their biodiversity impacts, which is essential for LCA. This is the case for the Biodiversity Footprint Methods and Calculator⁶¹. Some of the approaches are sector specific (Table 5).

Biodiversity offsets are conservation approaches used to compensate for the unavoidable impacts of a specific project or development plan on biodiversity⁶². By definition, biodiversity offsets aim to achieve no net loss of biodiversity, and preferably a net gain with respect to species composition, habitat structure, ecosystem function, and people's use and cultural values associated with biodiversity⁶³. Habitat area is a commonly used metric, typically multiplied by a value that refers to the condition of the habitat and/or its biodiversity importance (in terms of species richness, naturalness or potential to provide ecosystem services). Other type of metrics that are used focus on species and their needs (for example type of habitat, existence of predators, or diseases), are based on estimated replacement costs, or focus on ecosystem services (in biophysical, but also monetary, terms)⁶⁴. The choice of metric is generally dependent on the type of project being offset. This increases the possible coverage of biodiversity dimensions within the biodiversity offsets realm, but makes it more difficult to compare across biodiversity offset sites⁶². The lack of a direct link with production processes limits the use of this type of information in the LCA domain.

The Natural Capital Protocol⁶⁵ is a standardised framework for businesses to understand and develop their relationships with the environment, in terms of impacts and dependencies; this is similar to the national level environmental accounting framework, developed by the United Nations (see the SI: "Ecosystem services (ES) accounting approaches"). There are ongoing efforts to improve biodiversity considerations in the Protocol, particularly via target setting and indicator development⁶⁶.

The EBVs categories which are reflected by the methods increase in this area, as almost all dimensions of biodiversity are covered by at least two methods.

330 Most approaches focus on minimizing the negative impacts deriving from different drivers, such
331 as land use, deviations from nutrient cycles, infrastructure, habitat fragmentation, climate change
332 (linkable to LCA impact categories). However, some focus on the positive impacts. The Species
333 Threat Abatement and Recovery (STAR) Metric (previously known as Biodiversity Return on
334 Investment Metric - BRIM)⁶⁷ has the potential to show how interventions can deliver a reduction
335 in pressures, and therefore also to reduce a species' extinction risk¹². The LIFE Biodiversity Impact
336 Index + Positive Scoring^{68, 69} assessment also provides companies with specific actions for
337 reducing their impact on biodiversity.

338 **Table 5.** Recent approaches developed for quantifying biodiversity impacts of companies. Based on the reviews of Lammerant et al.
 339 (2018)¹² and Goncalves et al. (2014)⁶².

Name of the approach	Relationship with LCA impact category	Metrics* to assess biodiversity impacts directly or indirectly	Relationship with LCA approaches	Sectors covered	Relation to categories of EBVs	Lead developers
Global Biodiversity Score	<ul style="list-style-type: none"> • Land use • Climate change • Acidification • Eutrophication • Water use/stress 	Mean species abundance (MSA)	Use of process-based LCA database	Cross sectoral	Species populations	CDC Biodiversité ⁵⁹
Biodiversity Impact Metric	<ul style="list-style-type: none"> • Land use 	MSA	No	Cross sectoral	Species populations	Cambridge Institute for Sustainability Leadership ⁷⁰
Biodiversity Indicator for Extractive Industries	Case specific	Case specific (takes into account threatened species, critical habitat and protected areas)	No	Extractive Industries	Case specific	UNEP-WCMC ⁷¹
Product Biodiversity Footprint	<ul style="list-style-type: none"> • Land use • Water stress • Climate change • Terrestrial acidification • Freshwater eutrophication 	Potentially disappeared fraction (PDF) of species	Use of process-based LCA database; use of LC-Impact method ^{26,27}	Cross sectoral	Community composition	I Care & Consult, Sayar ⁶⁰
Biodiversity Footprint Approach	<ul style="list-style-type: none"> • Land use 	PDF of species	Use of ReCiPe method ²⁵	Financial Institutions	Community composition	ASN Bank ⁵⁸
Species Threat Abatement and Recovery (STAR) Metric (previously Biodiversity Return on InvestmentMetric)	No	Species extinctions	No	Cross sectoral	Community composition	IUCN ⁶⁷

Name of the approach	Relationship with LCA impact category	Metrics* to assess biodiversity impacts directly or indirectly	Relationship with LCA approaches	Sectors covered	Relation to categories of EBVs	Lead developers
Agrobiodiversity Index	No	7 biodiversity indicators: species diversity, varietal diversity, functional diversity, underutilised/local species, soil biodiversity, pollinator biodiversity, and landscape complexity	No	Agriculture	Genetic composition; Species populations; Community composition; Ecosystem structure	Bioversity International ^{72,73}
Biodiversity Footprint Method and Calculator	<ul style="list-style-type: none">• Land use• Climate change• Water use (only in Method)• Eutrophication (only in Method)	MSA	Not directly. LCA process-based database can be used in the case of absence of data from companies.	Cross sectoral	Species populations	Wageningen Environmental Research (Alterra) Netherlands Environmental Assessment Agency (PBL) Plansup Saxion ⁶¹
LIFE Impact Index + Positive Scoring	<ul style="list-style-type: none">• Land use	MSA	No	Cross sectoral	Species populations	LIFE Institute ^{68,69}
Biodiversity offsets	Case specific	Examples of metrics**: <ul style="list-style-type: none">• Habitat area• Habitat fragmentation• Net primary production• Nitrogen content• Soil pH• Survival rate• Emigration rate• Dispersal distance• Vegetation cover	No	Cross sectoral	Species populations; Species traits; Ecosystem structure; Ecosystem function; Community composition	-

Name of the approach	Relationship with LCA impact category	Metrics* to assess biodiversity impacts directly or indirectly	Relationship with LCA approaches	Sectors covered	Relation to categories of EBVs	Lead developers
		<ul style="list-style-type: none"> • Number of trees per size, per area • Species diversity 				

* in case of an index or composite indicator, metric refers to the metric used in the biodiversity component of the index or composite indicator

** Examples of metrics taken from a review by Goncalves et al. (2014)⁶²

3.2.3. Ecosystem services (ES) accounting approaches

The focus of this paper is on biodiversity, but due to the close interrelationship between biodiversity and ES⁷⁴, advancing the integrating ecosystem services in LCA is likely to be beneficial for improving biodiversity impact assessments. The structure of this section is somewhat different from the previous ones, since there have already been several reviews on the integration of ES into LCA^{19, 75, 76}. Here, we discuss a few background cases, and outline how recent advances in the ES field could contribute to better integrating these approaches into LCA, as well as how that could be used for a better coverage of biodiversity.

ES are how ecosystems contribute to human wellbeing. While human societies benefit from ES, human interventions may affect ES either negatively or positively (Figure 2). In contrast to what was stated in the Millennium Ecosystem Assessment (MA; 2005)⁷⁷, it is now commonly acknowledged^{78, 79} that the focus of ES is on ecological processes generating benefits rather than on the benefits themselves, which constitute the final outcome. ES are not a direct measure of biodiversity; however, they depend on the ecological processes directly supported by biodiversity. These ecological processes, in turn, are also essential for the conservation of biodiversity, putting ES in a bilateral relationship with biodiversity (Figure 2).

Figure 2. Bilateral relationships between human society and its interventions, ES, and biodiversity. The boxes with a bold border indicate terms that represent this relationship in LCA (natural resources, and ecosystem quality). The grey boxes indicate terms that represent this relationship in ecosystem accounting (ES and ecosystem condition). The white arrow represents the contributions from natural processes to human society; the light grey arrows represent contributions from natural processes to the environment; and the dark grey arrows indicate interventions from human society (positive or negative).

The distinction between ecological processes and the benefits derived from ecosystems helps to create analogies with LCA terminology, when considering midpoint and endpoint levels. These are presented in the SI.

As previously mentioned, the current LCIA models mainly quantify the impact of land use stressors on species richness, but do not assess contributions to human wellbeing. In their extensive review, Othoniel et al. (2016)¹⁹ suggest a series of actions that should lead the development of future LCIA to incorporate an ES approach. Among those suggested actions are the following: (i) to consider the interconnectedness of socio-ecological systems by coupling the ecological and economic sides; (ii) to model a spatially explicit ES, to better represent the flow between areas that provide ES, and ES beneficiaries (for example, the flow of the flood protection ES provided from

a wetland to a city); (iii) to include economic valuations; and (iv) to have a clear perspective on the relationship between biodiversity and ES indicators.

An accounting approach could greatly help in addressing most of these actions. Thus far, few attempts at tracking the relationship between LCA and integrated accounting systems^{75, 80} have highlighted the need for adequate information about the role of ES in supporting human activities, but even these works still lack an assessment and valuation of real ES flows.

On the other hand, recent advancements in accounting for real ES flows still do not make use of the LCA approach. Specifically, the System of integrated Environmental and Economic Accounting – Experimental Ecosystem Accounts (SEEA EEA) presents a framework to develop ecosystem and ES accounting tables^{81, 82}. SEEA EEA complements the core System of National Accounts (SNA) with a set of satellite accounts meant to systematically report data on:

- Ecosystem extent accounts, which show the opening and closing stock of different ecosystem types in physical terms, in a spatially explicit manner (e.g. in ha or km²)⁸³.
- Ecosystem condition accounts, which show the opening and closing stock in physical terms, with different indicators such as: species-based indicators as compositional characteristics, vegetation and biomass as structural characteristics, ecosystem processes as functional characteristics, physical and chemical states, and landscape patterns⁸⁴.
- ES accounts, which show the supply and use tables of different ES, classified according to the Common International Classification of Ecosystem Services (CICES) in physical and monetary terms. Some applications undertaken at a continental scale are available for Europe^{85, 86}.

ES supply and use tables particularly address the assessment of ES flow. As explained in La Notte et al. (2019)⁸⁷, ES potential represents what ecosystems can supply; once it interacts with ES demand, the actual ES flow is generated. Supply and use tables are compiled with ES actual flow, in such a way that the supply table shows which type of ecosystem the flow comes from, and the use table shows which users it goes to. The ES potential is often assessed through explicit biophysical models⁸⁸ which consider (case-by-case) the features that can count as driving variables (to set the cause-effect relationship), such as scale, and spatial connectivity. The ES demand is structured according to the SNA classification of economic sectors and households, and depending on the role of the actual ES flow (e.g. economic sectors' intermediate consumption, or households' final consumption), the flow chain facilitates identifying final beneficiaries throughout the core economic system.

By considering condition accounts and supply and use tables, it is also possible to clarify the relationship between biodiversity (expressed as a holistic indicator, for which the change between closing and opening stocks is measured), and the flow, which is assessed for individual ES (one-by-one). With condition accounts, it is only possible to measure the changes (and thus, the trends) over time; with ES supply and use tables, it is possible to establish a causality nexus between enabling pressures and users, and the ES actual flow. Of course, condition indicators assessing the status of biodiversity will be impacted by the changes in ES flows, and ES flows are affected by the status of biodiversity, especially when looking at maintenance services. Specifically, for an ES such as "habitat maintenance", ecosystem condition indicators define the initial status, which will affect the assessment of the service flow. Ecosystem and ES accounts seem to offer a good channel for merging the complexity of ecological issues with the policy power effectiveness of the LCA approach, in a transparent and structured way.

4. DISCUSSION

It is increasingly recognised that assessing the impacts of products and supply chains on biodiversity is crucial both for biodiversity conservation, and to move towards sustainable patterns of production and consumption. This is reflected in several policy domains (e.g. the Aichi Targets, Sustainable Development Goals, and the EU's Biodiversity Strategy)⁸⁹, as well as in the research community increasing levels of interest. LCA is considered to be the standard methodology for assessing the environmental impacts of products, taking into account their whole life cycle.

Different communities are responding to the need for biodiversity metrics and indicators to be developed and applied to different systems (e.g. product, corporate, value chains, regions, and country). However, the challenge of developing a relatively simple and understandable metric whilst keeping a sound ecological relevance is substantial.

Despite the increasing interest in assessing biodiversity impacts through LCIA methods, there are still many limitations and gaps in this area (as highlighted in^{13, 14, 44, and 90}). Operational endpoint methods do not cover all of the drivers of biodiversity loss; specifically, they do not include impact pathways for the introduction of invasive species, or for the overexploitation of resources. Impacts on biodiversity are quantified in terms of species richness loss, which mainly refers to the EBVs "community composition" category. Other dimensions that characterise biodiversity (e.g. genes diversity, species abundance, and ecosystems diversity) are therefore missing. Concerning the spatial scale, for the sake of applicability, country level impacts are chosen. However, biodiversity changes in reality do not necessarily match with country limits. While ecoregions could better represent the distribution of biodiversity at the species level, the appropriate scale is dependent on the dimension of biodiversity covered, and on the impacts being assessed (e.g. very local biodiversity impacts due to wind turbines).

Recent single endpoint studies address some of the improvements suggested regarding modelling the impacts from land use (land use intensity, and habitat fragmentation). However, the biodiversity dimension analysed still relates to community composition via species richness. Hanafiah et al. (2013)⁴⁷ developed an impact assessment model to include the impacts of invasive species on biodiversity. However, the model has not been implemented within operational LCIA methods¹⁴, despite invasive species being one of the most important drivers of biodiversity loss. Promising developments are occurring at the midpoint level, for example the development of novel biodiversity indicators, inclusion of marine biodiversity, and new approaches to address biotic resource use. Nevertheless, more work is required to further model the impact pathways from midpoint towards endpoint, and to extend the spatial coverage of impacts.

Other life cycle-based approaches have mainly addressed land use and climate change as drivers of biodiversity loss. Some studies present new metrics of biodiversity loss that can be adopted in LCIA, such as MSA or missing individual bird species. The former would add information beyond species richness, while the latter would add detail to current LCA modelling. Adopting these metrics into LCIA would pose its difficulties as, for example, both metrics are built on spatially explicit impact assessments.

Our analysis of approaches adopted and developed by businesses, both within and beyond the LCA domain, showed that many approaches rely on data from LCA process-based or input-output databases and LCIA models, but that LCA is rarely used as the single approach to quantify biodiversity impacts. This suggests that current LCA methods to quantify biodiversity impacts are not yet fully adequate to address business needs. Many of the approaches developed in the business domain use MSA to quantify biodiversity impacts, suggesting that this metric should be including in LCA. However, the methods used by this metric present certain shortcomings, for instance, the

environmental cause-effect chain underpinning GLOBIO is built on data from the most frequently studied species and ecosystems. Moreover, it does not account for impact pathways on marine biodiversity, impacts due to chemical pollution, and the introduction of invasive species. GLOBIO uses spatial information on environmental drivers, which can be helpful to identify and improve the spatial granularity of the link between the pressures and impacts. However, it is not yet suitable for LCA. Chaplin-Kramer et al. (2017)⁹¹ substituted the key elements of the life cycle inventory (LCI) with outputs from predictive land-change modelling, and spatially explicit ES models to quantify the impacts on biodiversity using MSA. When compared with current approaches in LCA, their new approach (Land Use Change Improved (LUCI)-LCA) yielded very different results, showing the importance of including the spatial information for where there will be land use impacts.

Another aspect that can be seen as a limitation of LCA in the business context is that this method was not designed to present beneficial biodiversity impacts, which instead is addressed by several indicators developed by businesses¹². In fact, LCA is based on inventories of pollutants that by their very nature pollute the environment, with no beneficial effects. LCA can either show avoided impacts, specifically from recycling or reusing materials, or simply present an impact in a comparatively positive way, such as when a product has "less negative impact" than another. However, the latter cannot be defined as a positive impact, as this would have to be an action that enhances an environmental characteristic. For instance, a negative impact occurs when an area loses species after a human intervention (e.g. deforestation), while a positive impact is when an area gains species after an intervention (e.g. reforestation, following investments – as the STAR Metric quantifies).

Currently, the available LCIA methods already address some impacts on ES. Alejandro et al. (2019)⁹² identified five mid-point impact categories in ReCiPe2016 directly linked with specific ES (regulation and provisioning services). Conceptually, ES can be approached in LCA from two distinct angles. The more usual approach is to quantify how ES are impacted by output flows coming from the technosphere, thus considering them in the LCIA stage. However, by definition ES relate to how ecosystems contribute to human wellbeing, therefore they can also be considered as inputs to the production processes, and hence accounted for in the LCI.

Recent advances in ecosystem accounts, under the framework of the United Nations SEEA EEA can provide important information for improving how LCA cover ES. Linking ecosystem condition accounts (which provide information on ecological indicators at different levels, for example species, landscape, and functional), with ecosystem extent accounts (which show the opening and closing stock of ecosystem types) can help to clarify the necessary environmental cause-effect chains for developing characterisation factors for LCIA⁸⁷. ES accounts can provide information directly relevant for LCI by quantifying the flows of ecosystem services to economic sectors. Considering condition accounts and ES accounts can also help to clarify the relationship between biodiversity and ES. Indicators from condition accounts which assess the status of biodiversity will be impacted by the changes in ES flows, and ES flows are affected by the status of biodiversity, especially when looking at maintenance services.

Establishing synergies between ecosystem accounts and the LCA framework can be facilitated by discussions on the current use of the ES cascade model to improve the coverage of ES in LCA, since the ecosystem accounts share a similar structure with the cascade model. Integrating the ES

cascade model into the LCA framework can provide guidance concerning (i) a definition of LCI flows for ecosystem services^{80, 93}, (ii) a clarification of the steps and processes to be included in the LCIA cause-effect chain modelling^{80, 93, 94}, (iii) an understanding of the interactions between ES and socio-economic systems^{80, 93} and finally (iv) a definition of costs and benefits (in monetary terms)^{80, 93}. Synergies between ecosystem accounts and the LCA framework can also be facilitated by a recently developed framework for LCA based on the techno-ecological synergy (TES-LCA) framework⁹⁵, the TES-LCA⁹⁶. The TES-LCA framework incorporates the demand and supply of ecosystem services across multiple spatial scales allowing to determine overuse of ES and identify decisions, along the value chains, with possible positive impacts on ES. The TES-LCA framework expands the conventional LCA framework, at LCI level, by including the inventory of ecological systems and allocation of ES between users, and at LCIA level, by calculating sustainability metrics based on ecological overshoots, and by quantifying the flows of environmental impacts not mitigated by ecosystems.

5. FINAL REMARKS

This work has reviewed existing frameworks, models and metrics, within and beyond LCA, in order to find possible links and convergences that can improve the assessment of value chains' impacts on biodiversity.

LCIA operational methods are limited in assessing biodiversity impacts, as only one dimension of biodiversity is assessed (community composition). There are currently multiple advances taking place in the LCA community, for example, the integration of more biodiversity dimensions (ecosystem structure, ecosystem composition, species traits, species populations), moving beyond terrestrial biodiversity (marine biodiversity is starting to be addressed), the inclusion of land use intensity metrics, and the development of spatially explicit inventories. In the time of the

information revolution, it is important to systematise these advances, ensuring that the community makes the most of them, and integrates them as quickly as possible into operational LCIA methods.

Efforts to quantify biodiversity impacts through other approaches can also benefit the LCA community; in fact, by sharing some of LCA's methodological principles, they offer great potential for further integration into LCA. Approaches developed by businesses to account for biodiversity impacts are not necessarily consistent with LCA, however, they offer insights into businesses' needs and motivations. Many of the approaches which have been developed, or are under development, by businesses make extensive use of life cycle and input-output databases and LCIA methods, coupled with external biodiversity components. As a result, it is also advisable that the LCA community cooperates with these communities to make sure that further developments make LCA outputs, in terms of quantifying biodiversity impacts, more relevant to the business community.

Recent advances in ecosystem accounting can be beneficial to LCA, thanks to the coverage of ES, as well as biodiversity. The set of ES accounts available in the SEEA EEA provides information on the extent and condition of ecosystems at the beginning and end of the accounting period, and on the ES flows to economic sectors. This allows for changes to be tracked over time, establishing causal relationships between ecological and economic indicators.

While there are many opportunities for improving biodiversity coverage in LCA, some challenges also emerge. Within LCA, it is important to take stock of existing methods, understand the value of each, and the potential differences between them. Some crucial aspects of coupling LCA with other methods are: (i) consistency across spatial scales, (ii) consistency across system

561 boundaries, (iii) the use of heterogeneous data, and (iv) identifying a causal relationship between
562 biodiversity loss and impacts from producing sectors.

563 There are various existing frameworks for biodiversity impact assessment. In this study, we add
564 to the literature by analysing frameworks developed within other life cycle, business, and
565 accounting frameworks. Future frameworks to be analysed are within the policy realm, as
566 measuring progress towards specific policy targets is normally done via sets of indicators. For
567 example, the CBD suggested a set of more than 100 indicators⁹⁷ to measure progress towards the
568 Aichi Targets, covering multiple aspects of biodiversity, biodiversity loss, and several taxa. The
569 IPBES released a suit of core and highlighted indicators^{98, 99} to be used in regional and global
570 assessments on the state of biodiversity and ES. These indicators were to monitor progress towards
571 the SDGs¹⁰⁰, which also present good opportunities for synergies, covering not only biodiversity
572 loss (SDG 15), but also sustainable production and consumption (SDG 12). Sectoral policies can
573 be an additional source of information, by linking the environmental indicators to the sector
574 involved. For example, the European Union's (EU's) Common Agricultural Policy (CAP)
575 provides a set of indicators for assessing the performance of biodiversity policies (e.g. Farmland
576 Bird Index)¹⁰¹.

577 LCA provides a systematic framework for assessing value chains, where it is important to
578 capitalise on the scientific knowledge developed in specific domains. When assessing impacts on
579 biodiversity, this can prove to be a very difficult task, especially as the discussion on metrics is an
580 open debate within and beyond the ecological domain. Nevertheless, focusing on scientific
581 knowledge to assess impacts on biodiversity is very essential, as neglecting a value chain approach
582 in addressing drivers and impacts may lead to misleading results on where to act to conserve local
583 and global biodiversity.

6. ASSOCIATED CONTENT

Supporting Information. A .pdf file is available, including a detailed description of the analysed literature, the main terminology used in the LCA context, and a table summarising the coverage of impact drivers for existing and operational LCA methods.

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All authors contributed to the writing of the manuscript. All authors have given approval to the final version of the manuscript.

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Drivers of biodiversity loss

- Land use/Land use change
- Climate Change
- Pollution
- Overexploitation
- Invasive and alien species

Metrics: PDFs, PAFs, Kgs per year, hemeroby, occupied ranges, etc.