Quantification of Biodiversity in Life Cycle Analysis

Literature assessment on the latest developments for biodiversity quantification in LCA frameworks.

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Public summary

We all know human activities are having a negative impact on global warming. But have you ever thought about the impact of your food, clothing or your daily car ride on the animals, plants, insects, etc. living on Earth? Awareness on sustainable lifestyle is growing and consumers are more and more interested in making ‘the right choice’. However, how do you decide what, for example, type of clothing is less harming for biodiversity than the other? Since the consumer is asking this question, companies are too. How can they decide what is the most sustainable way to produce their product? Could they use an alternative resource, or does a change in the production process or shipping make for a more sustainable product or service? Luckily, there are already calculation methods that can provide useful insights into these questions. Life Cycle Analysis (LCA) is a method that provides information and allows for the evaluation of environmental impacts throughout the product’s life cycle. In four steps, the goal and scope of an assessment are defined, data is collected, impacts are calculated, and conclusions are drawn to make better business decisions. It creates a complete product assessment, from the very first to the very last life stage of the product.

In the last two decades, many great improvements have been made to the LCA methodology. However, measuring biodiversity remains a challenge. In the third step of an LCA, the life cycle impact assessment (LCIA), the impact on biodiversity can be quantified. A difficulty for LCA methodology, in general, is a lack of specific data. Therefore, all LCA methods have to make some concessions and assumptions in order to represent the environment as realistic as possible. This literature assessment assesses five methods on how they address four important knowledge gaps in biodiversity quantification. The five methods are introduced individually, their general framework and how they tackle biodiversity quantification is explained. Afterwards, it is shown how each knowledge gap is addressed by the methods. This assessment shows that although improvements have been introduced for all gaps in the last few years, some are better covered than others. Altogether, LCA results should always be interpreted with care and with acknowledgement for the value choices, hypotheses, and limitations.

Abstract

Research on biodiversity loss due to human activities has gained serious interest because of major decrease in biodiversity over the last century. Life Cycle Analysis (LCA) is a widely used multistep management tool to assess the environmental impacts of the entire life cycle of a human artefact: a product, a service, or an activity. In four steps, the goal and scope of an assessment are defined, data is collected, impacts are calculated, and conclusions are drawn to make better business decisions. It creates a complete product assessment, from the very first to the very last life stage of the product. In the third step of an LCA, the life cycle impact assessment (LCIA), the impact on biodiversity can be quantified. Biodiversity quantification is hard, generally, because of lacking data. ReCiPe2016 is an LCA method mainly used in the Netherlands nowadays. Since ReCiPe2016, development on biodiversity quantification has been ongoing.

This literature assessment includes five methods: ReCiPe2016, IMPACT World+, LC-IMPACT, PBF, and BIA+. The methods are assessed on how they address the four main knowledge gaps for biodiversity quantification: ‘species diversity’, ‘spatial resolution assessment vs data’, ‘drivers for biodiversity loss’, and ‘trade-off LCA and biology’. The five methods are introduced individually, their general framework and how they include biodiversity quantification is explained. Afterwards is shown how each knowledge gap is addressed by the methods. This assessment shows although improvements have been introduced for all gaps in the last few years, some are better covered than others. Future development on biodiversity in LCA would be to include ecosystem services and positive impacts on biodiversity. Altogether, LCA results should always be interpreted with care and with acknowledgement for the modelling choices, hypotheses, and limitations.

Contents

1. Introduction

Since 1970, there has been a 68% global biodiversity decline of mammals, birds, fish, reptiles, and amphibians (WWF, 2020). Because of this major decrease in biodiversity, research on how human activities impact biodiversity has gained increased importance. Human activity can affect biodiversity directly by activities such as plastic package littering (Dias, 2016), transport processes causing biological invasion (Schenk, 2001), and agricultural production leading to land use (Michelsen *et al.*, 2012). On the other hand, indirect human activities, such as the release of nanomaterials by pharmaceutical products (Som *et al.*, 2010), can also have a negative impact on biodiversity. Therefore, it is important to research the impact size of human activities on declining biodiversity.

Life Cycle Analysis (LCA) is a widely used multistep management tool to assess the environmental impacts of the entire life cycle of a specific human artefact: a product, a service, or an activity. It is a factual analysis of all the life cycle stages of a functional unit in terms of sustainability, as the life cycle can have an environmental impact in many ways. An LCA provides information and support in finding possible answers to environmental problems and allows the evaluation of environmental impacts of the artefact's life cycle, from the very first to the very last life stage. The complete process of LCA includes goal and scope definition, inventory analysis, impact assessment, and interpretation. First, the goal and scope of the assessment are defined to ensure the LCA is performed consistently. Second, the in- and outputs of the associated system are quantified in the inventory analysis. In the third step, during the life cycle impact assessment (LCIA), the emissions and resource extractions are translated into a limited number of environmental impact scores through the use of characterization factors (CFs). CFs indicate the environmental impact per unit of stressor. Environmental impacts are then classified and evaluated, and conclusions are drawn to make better business decisions. Lastly, the conclusions are checked and interpreted and ready to share with the world.

Over the last two decades, LCIA methodologies were developing quickly to increase the completeness, accuracy, and reliability of the impact assessment. These methods allow for a translation of the inventory flows of a given life cycle into a limited number of environmental impact scores through the use of CFs. Sets of CFs are typically available to practitioners in the form of LCIA methods that can be implemented into LCA software. The outcomes of this translation express the environmental effect of an artefact in specific impact categories at two levels: midpoint or endpoint level. The midpoint categories are problem-oriented and can be transformed to endpoint category results, while the endpoint categories are damage-oriented that calculate the potential damage on the so-called areas of protection (AoPs): 'human health', 'ecosystem quality', and 'resource scarcity' (Fig. 1). These AoPs form the basis of decisions in policy and sustainable development (Goedkoop *et al.*, 2009). LCIA combines an array of impact categories to obtain a single unit to indicate the impact of a human artefact.

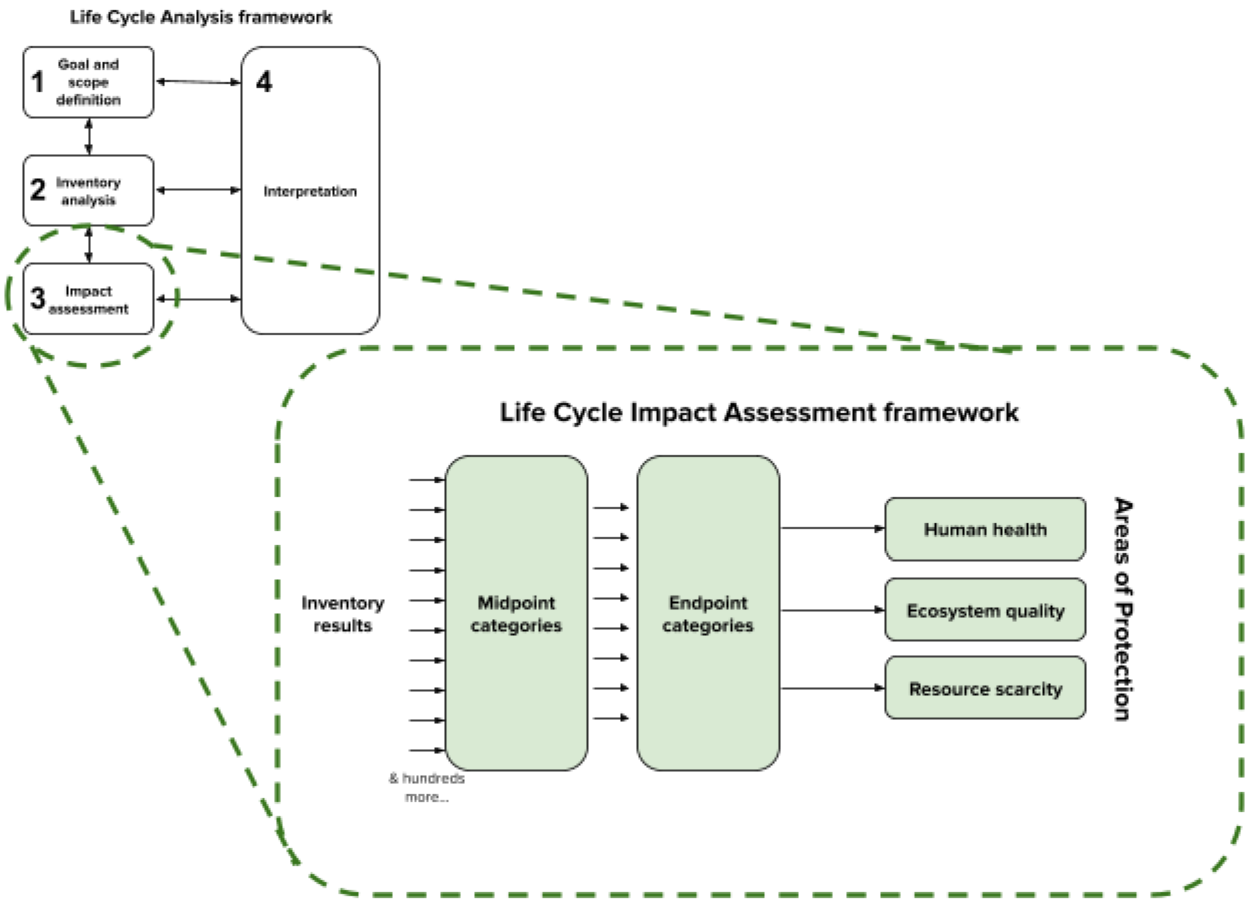

Figure 1. Overview Life Cycle Analysis and its (LCA) and Life Cycle Impact Assessment (LCIA). The general LCA framework is shown in the top left corner. The third step of the LCA, Life Cycle Impact Assessment LCIA, is highlighted in the left bottom corner. In the LCIA, the inventory results are transformed to damage on the three Areas of Protection (AoPs): 'human health', 'ecosystem quality', and 'resource scarcity'.

Biodiversity is hard to quantify properly in an LCA, generally because of lacking data. The few impact assessment methods that include biodiversity impacts, are all plagued by one or more of the following gaps or weaknesses: species diversity, spatial resolution of impact assessment models versus spatial resolution of inventory data, impacts of only three drivers (mostly land use) for biodiversity loss, and trade-off between biology and LCA (Winter *et al.*, 2018). These knowledge gaps illustrate the difficulty when it comes to quantifying biodiversity in an LC(I)A. Since the latest release of ReCiPe in 2016, LCIA methodology and its regard to biodiversity has been developed further. In this literature assessment, the aspects regarding biodiversity quantification in five methods are assessed: ReCiPe2016 (Huijbregts *et al.*, 2017), IMPACT World+ (Bulle *et al.*, 2019), LC-IMPACT (Verones *et al.*, 2020), Product Biodiversity Footprint (PBF; Asselin *et al.*, 2020), and Biodiversity Impact Assessment (BIA+; Winter *et al.*, 2018). It discusses how the methods address the four knowledge gaps and show where improvements are needed in further LCIA development to capture the most biodiversity impact.

First, the ‘literature selection’ will elaborate on how this literature assessment has been set up. In the ‘3. Methods quantifying biodiversity’ section, five methods will be presented. For each method, the general framework will be explained and followed by an explanation of how the method allows for biodiversity quantification. The extent by which each knowledge gap is addressed in the methods will be discussed in ‘knowledge gaps biodiversity quantification’. From this, an overview and future prospect is given regarding biodiversity quantification in LCA between 2016 and 2021.

2. Literature selection

This literature assessment is based on a selection of literature in the field of biodiversity within Life Cycle Analysis (LCA) methodology. Models developed since ReCiPe2016 have been collected via web search (2017-2021; Google Scholar search terms: 'biodiversity in life cycle (impact) assessment' and 'biodiversity quantification (in life cycle (impact) assessment))'. This search was used to inventorise the most researched or developed LCIA methods regarding biodiversity impact. The literature search was extended by including the studies cited in the identified papers. Three studies with focus on marine biodiversity only were excluded from this literature assessment (Dorber *et al.*, 2019; Woods *et al.*, 2019; Turgeon *et al.*, 2021). From the collected studies, the improvements and main knowledge gaps over this time period could be identified and analysed.

Alongside ReCiPe two other LCIA methods have been developed and improved continuously over the past two decades, IMPACT World+ and LC-IMPACT. Their most recent versions from 2019 and 2020, respectively (Bulle *et al.*, 2019; Verones *et al.*, 2020), were included to illustrate the development of LCIA methods since ReCiPe2016. IMPACT World+ uses a midpoint approach, while LC-IMPACT uses an endpoint approach. Two additional methods, PBF and BIA+ (Asselin *et al.*, 2020 and Winter *et al.*, 2018), were included that solely focus on biodiversity within LCA to gain more in depth knowledge regarding the knowledge gaps in biodiversity quantification. PBF is based on the principles of LC-IMPACT, but presents a more alternative approach. BIA+ aims to cover all four knowledge gaps and also uses an alternative approach for this. The five methods were reviewed on their ability to cover the four knowledge gaps, 'species diversity', 'spatial resolution', 'impact drivers', and 'trade-off' that were identified by Winter *et al.* in 2018.

3. Methods quantifying biodiversity

A couple of LCA methods have been developed over the last 25 years. The earliest methods were published before the start of the century, and improvements have been published regularly since then (Fig. 2 & Tab. S1). References and aims of the studies can be found in Supplementary Table S1. This overview shows several other methods have been developed over the years besides ReCiPe2016. IMPACT World+ (Bulle *et al.*, 2019) and LC-IMPACT (Verones *et al.*, 2020) are the latest updates on complete LCIA methods while PBF (Asselin *et al.*, 2020) and BIA+ (Winter *et al.*, 2018) are the latest updates with specific focus on biodiversity within LCIA. In the results, the framework of the five methods will be explained and the inclusion of biodiversity within each method will be highlighted.

N.B. If the reader is familiar with the five methods, reading can be continued in section '4. Knowledge gaps biodiversity quantification'.

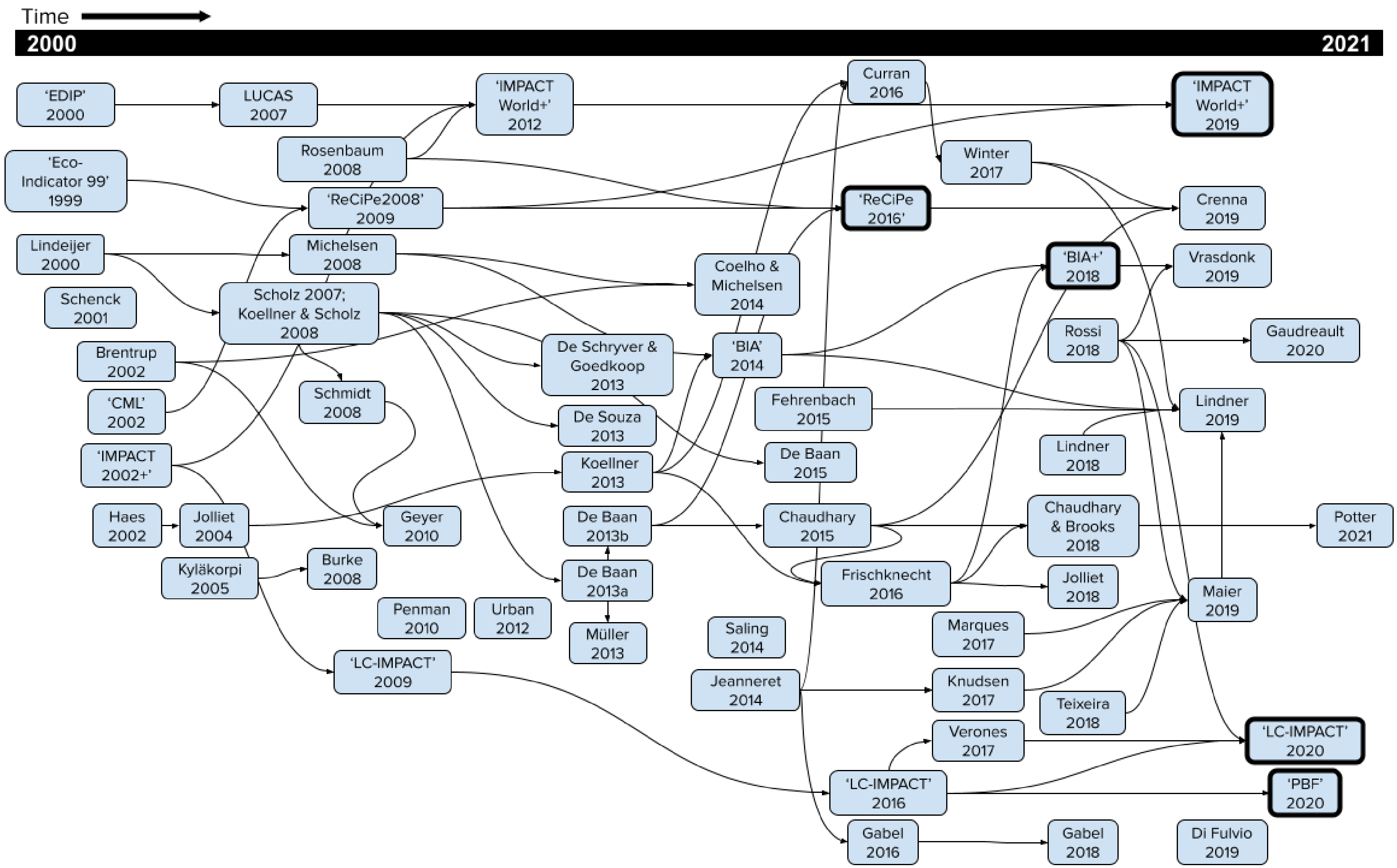

Figure 2. Timeline overview of articles and methods related to life cycle impact assessment (LCIA) frameworks considering biodiversity. Studies that support future studies are connected with a black arrow. The assessment methods used in this literature assessment are indicated by a thickened line surrounding the box. Figure adapted after Gabel *et al.* (2016) and extended with articles addressing biodiversity in LCA from 1999 to 2021. References and the aim of each study can be found in the Supplementary Table S1.

3.1. ReCiPe

ReCiPe2016 is a harmonised LCIA method at midpoint and endpoint level that is often used in the Netherlands and the rest of Europe. In 2008, the first ReCiPe method was developed by cooperation between the Dutch National Institute for Public Health and the Environment (RIVM), Radbound University Nijmegen, Leiden University (Centrum Milieukunde Leiden, CML) and Pré Consultants (Goedkoop *et al.*, 2009). These collaborators also form the name of this method with their initials: "R_C_P_". After several years, an updated version of this method was published, ReCiPe2016 (Huijbregts *et al.*, 2017). The model follows the same model framework that was proposed in ReCiPe2008. At the start of this century, two methods were mainly used in LCA methodology; CML from Centrum Milieukunde Leiden and Eco-Indicator99 from Pré Consultants. CML was presented as a baseline method for characterisation and uses the midpoint approach, while Eco-indicator99 focuses on the interpretation of results and uses the endpoint approach. In 2000, after a special session, 50 LCA experts concluded it would be eligible to combine these two approaches in one framework after assessing the strength and weaknesses of both methods. The combination of the CML and Eco-Indicator99 methods formed the basis for the ReCiPe method in 2008. ReCiPe2008 could literally be used as a recipe to calculate life cycle impact category indicators, and was useful to obtain in-depth knowledge of LCIA and the underlying rationale. The combination of both mid- and endpoint approaches allows the LCA practitioners to calculate environmental profiles at either level, depending on the scope of the LCA study (Bulle *et al.*, 2019).

The updates in ReCiPe2016 provide CFs that are representative for the global scale instead of the European scale, while maintaining the possibility for a number of impact categories to implement CFs at a country and continental scale (RIVM, 2017). On top of this, working with the same time horizon per cultural perspective across the various impact categories allows for enhanced consistency in the development of mid- and endpoint models.

The number of environmental interventions was also expanded, and several impact pathways were added. The areas of protection (AoPs) in the ReCiPe2016 framework are 'human health', 'ecosystem quality', and 'resource scarcity'. 'Human health' damage is represented in years that are lost or that a person is disabled for due to a disease or an accident, in disability adjusted life years (DALYs). 'Ecosystem quality' is used to represent biodiversity in local relative species loss integrated over space and time in potential disappeared fraction (PDF). The unit for terrestrial ecosystems is PDF of species·m^2·year, and for freshwater and marine ecosystems PDF of species·m^3·year. Species densities were included to combine the impacts of these three ecosystem-types into a single unit, species·year (method Goedkoop *et al.*, 2009). 'Resource scarcity' is represented by the extra costs, in dollars ($), that are involved for future mineral and fossil resource extraction.

3.2. IMPACT World+

IMPACT World+ is developed after the increasing need for a regionalised LCIA method covering the entire world and is the updated LCIA framework version of the IMPACT 2002+, LUCAS and EDIP methods (Jolliet *et al.*, 2003; Toffoletto *et al.*, 2007; Hauschild *et al.*, 2001), respectively). It is a midpoint-endpoint framework that distinguishes four complementary viewpoints to present an LCIA profile. Next to the midpoint impacts, damage impacts, and damages on the three AoPs ('human health', 'ecosystem quality', and 'resources & ecosystem services'), a fourth viewpoint is added. This viewpoint expresses two areas of concern (AoCs) regarding water- and carbon-related damages to the 'human health' and 'ecosystem quality' AoPs. The water and carbon AoCs represent areas of particular interest to stakeholders or society. The rest of damages on human heald and 'ecosystem quality' are also covered in this AoC viewpoint. The AoCs consist of six sub-AoCs: 'carbon human health', 'water human health', 'rest of human health', 'carbon ecosystem quality', 'water ecosystem quality', 'rest of ecosystem quality'. To avoid double counting, AoCs can be used to complement AoPs by grouping impact scores of endpoint categories in by AoC within each AoP.

IMPACT World+ provides four sets of CFs in a consistent framework for all regionalised impacts at four scales: global, continental, country and native resolutions. This allows the IMPACT World+ practitioner to account for spatial variability, and identity and prioritise the to be regionalised elementary flows, which increases the discriminating power of LCA (Bulle *et al*., 2019). It also shows that several impact categories account for the most impact on biodiversity. Biodiversity is also represented by the AoP 'ecosystem quality' in PDF·year. 'Climate change' and 'land use' have the most dominant impact on 'ecosystem quality'. 'Marine acidification' and 'freshwater ecotoxicity' are the second-highest contributors to 'ecosystem quality' (Bulle *et al.*, 2019).

3.3. LC-IMPACT

LC-IMPACT is the most recently developed LCIA framework using an endpoint approach (Verones *et al.*, 2020). After de EU-FP7-funded project "Development and application of environmental Life Cycle Impact assessment Methods for imProved sustAinability Characterisation of Technologies" (LC-IMPACT), new models for impact ways and more regionalisation of impact pathway models were included in the LCIA framework. This provides the practitioner with one consistent and transparently documented LCIA method. The LC-IMPACT method was developed with the aims (1) to collect and develop characterisation models for all available impact pathways and to use these models to provide regionalised CFs with global coverage at category-specific, country, continental, and global scale, (2) to be able to include species extinction in the 'ecosystem quality' assessment, and (3) to provide well-defined sets of CFs based on value choices consistently implemented across categories (Verones *et al.*, 2020).

The time perspectives of this method give the LCA practitioner the choice between ‘core’ and ‘extended’ approach, depending on the goal and scope of the LCA (Asselin *et al.*, 2020). The ‘core’ approach uses a set of CFs considering 100 years of impacts while the ‘extended’ approach longer term impacts (∼1000 years). Both approaches can be combined, with the level of evidence of impacts that creates the choice between ‘impact with high degree of scientific confidence’ or ‘all impacts included’ (Goedkoop *et al.*, 2009; Verones *et al.*, 2020). This results in four possible sets of CFs: ‘all impacts - long term’, all impacts - 100 years’, ‘certain impacts - long term’, and ‘certain impacts - 100 years’. These sets make the application of CFs more transparent towards the consequences of key value choices.

LC-IMPACT also covers three AoPs: ‘human health’, ‘ecosystem quality’, and ‘natural resources’. Additionally, ‘ecosystem quality’ is subdivided in three ecosystem types: ‘ terrestrial’, ‘freshwater’, and ‘marine’. The impact categories have spatialised CFs when required. Some impact categories, in this method ‘climate change’, ‘stratospheric ozone depletion’ and ‘mineral resource extraction’, cover impacts independently of the place of emission or extraction (Verones *et al.*, 2020). Therefore, these impact categories have only global CF. The other impact categories have spatialised CFs on four levels: native, country, continental, and global.

Biodiversity can be quantified with the ‘ecosystem quality’ AoP in potentially disappeared fraction of species over time in PDF·year (Woods *et al.*, 2017). There is special focus to quantify a consistent global PDF in order to reflect global extinction of species, not local or regional. This is important, as if a species goes extinct in a certain location, it does not necessarily mean global extinction. The use of vulnerability factors to address global extinction, seen in this method, is not seen in ReCiPe2016 or IMPACT World+ (Verones *et al.*, 2020). Both regional and global assessments are required for a complete assessment. The global assessment is needed to avoid irreversible loss of biodiversity and the regional assessment to make sure ecosystems can maintain their functions (Verones *et al.*, 2020).

3.4. Product Biodiversity Footprint (PBF)

Product Biodiversity Footprint (PBF) is an LCIA method that guides decision-making in product design with a focus on biodiversity (Asselin *et al.*, 2020). It was first developed in 2016 by I-Care & Consult and Sayari in a private public partnership funded by the French Environmental Protection Agency and the companies L’Oréal, Groupe Avril, and Keering (Verones *et al.*, 2016). The method provides the practitioner with quantitative indicators based on cause-effect chains. If common LCA indicators are not sufficient, the indicators should be refined based on literature and ecological data. This allows the method to include all five drivers on biodiversity loss from Secretariat of the Convention on Biological Diversity (1. habitat change, 2. climate change, 3. pollution, 4. overexploitation and unsustainable use, and 5. invasive species; SCBD, 2010), albeit with a semi-quantitative or qualitative approach instead of a quantitative approach.

PBF consists of three modules. In the first module, three of the five SCBD drivers are assessed ('habitat change', 'pollution', and 'climate change') and the hotspots along the product value chain are identified. The second module focuses specifically on the impact of 'habitat change' on biodiversity through the impact category 'land use'. These results are combined with those from the first module. In the third module, the two remaining drivers are addressed with the indicators 'invasive species' and 'species management'. The combination of these modules allow the practitioner to compare two variants of a product to support ecodesign.

The first PBF module includes features derived from the LC-IMPACT method (Verones *et al.*, 2016). 1) The impact pathways from the endpoint impact categories to the 'ecosystem quality' AoP were used to account for the latest development in LCIA spatialisation. 2) The impact of these pathways is also expressed in the same unit for biodiversity loss, namely PDF·year. 3) The impacts related to 'land use' are assessed according to the method recommended by the United Nations Environment Programme – Society of Environmental Toxicology and Chemistry (UNEP/SETAC; Frischknecht *et al.*, 2016). PBF uses native spatial resolution specific to each impact category and includes two time horizons. The first time horizon assesses with a limit of 100 years, while the second one uses an extended time horizon of approximately 1000 years. At the start of the assessment, one of the time horizons is chosen and is applied consistently across all impact categories (Asselin *et al.*, 2020). The impact categories 'land occupation', 'land transformation', and 'water stress' (from LC-IMPACT) are combined to get the results for the SCBD driver 'habitat change' in PDF_{glo}·year. For the 'pollution' and 'climate change' drivers, the corresponding impact categories ('photochemical ozone formation', 'terrestrial acidification', 'freshwater eutrophication', and 'climate change', respectively) are expressed in PDF_{reg}·year for a regional perspective.

In the second module, ecological data and literature is used to account for practises impacting habitats consistently with the first module. This allows the practitioner to distinguish between practices regarding different types of products and different variants of products. However, more detailed subcategories are required than the six land categories specified for 'land use' impacts in the most recent methods LC-IMPACT, ReCiPe2016, IMPACT World+ (Asselin *et al.*, 2020). The land categories are 'primary forest', 'secondary forest', 'permanent crops', 'annual crops', 'grassland', and 'urban land'. For these (sub)categories, many practices are not reported in life cycle inventory databases and not assessed through LCIA CFs (Asselin *et al.*, 2020). In three steps, the potential biodiversity loss is used to adjust the LC-IMPACT CFs to CFs applicable to the subcategories. The potential species loss is calculated only for species richness and CFs of the 'land use' subcategories are expressed in $PDF_{glo}\cdot yr/m^2$ for 'land occupation' and in PDF_{glo}/m^2 for 'land transformation'. This provides the LCA practitioner with updated CFs for 'land occupation' and 'land transformation' compatible with other LCA impact categories in full LCA studies.

The third module covers the 'invasive species' and the 'overexploitation of species' SCBD drivers through the semi-quantitative indicators 'invasive alien species' and 'species management', respectively. The latter indicator also covers some pressures not covered by the LCA indicators in the ‘change of habitat’ driver in the first two modules, such as threatened species and socio-cultural value of species. The impact scores of subindicators are then assessed and qualitatively scored by the level of impact (potential impact or risk; scored 1 to 6) and the level of actions (actions to minimise risk of impact; scored 1 to 7).

The results of these impact scores can be visualised in spiderweb diagrams per impact pathway and per SCBD driver. In the impact pathway spiderweb diagram, seven LCA impact categories and the two remaining SCBD drivers are included. The other spiderweb diagram included the five SCBD drivers. The reference system is set at 100% and final results are displayed relative to this. Both diagrams illustrate the differences between the reference product and the variant of the product assessed.

3.5. Biodiversity Impact Assessment (BIA+)

The Biodiversity Impact Assessment (BIA+) is a methodological framework for screening biodiversity including all three levels of biodiversity (species, genetic, ecosystem). This method allows LCA the practitioners to assess currently missing impacts on biodiversity on a global scale (Winter *et al.*, 2018). The predecessor of this method, BIA, was published in 2014 (Lindner *et al.*, 2014) and is based on the UNEP/SETAC guideline on global land use impact assessment on biodiversity and ecosystem services (Koellner *et al.*, 2013). Inspired by the principles of Michelsen (2008) and Lindner *et al.* (2014), the BIA+ method determines biodiversity as the product of the habitat factor (HF) and the biodiversity status (BS): Biodiversity = HF x BS. In this formula, the HF represents a weighting for different regions of the world. Due to this, certain habitats can be weighted higher than others (Winter *et al.*, 2018). The BS captures the condition of biodiversity in a habitat. In this way, both the environmental conditions and the quality of the biodiversity in a given area is accounted for. The impact from a given human activity on biodiversity at a specific habitat is expressed as the product of the HF in that habitat and the change the activity induces in the biodiversity status of the specific habitat (Winter *et al.*, 2018). The status before (BS_0) and after (BS_1) impact account for the change in biodiversity status. This reference state before human impact should be defined in advance.

For the calculation of the HF, data from the World Wide Fund (WWF) is used. The WWF defined 827 ecoregions around the world that they divided into major habitat types (MHTs). At the time of the BIA+ development, there were 14 MHTs, but nowadays 26 MHTs are defined (WWF, 2022). These MHTs account for the spatial resolution in BIA+ (Winter *et al.*, 2018) as they describe different areas of the world. Within each MHT, the ecoregions have corresponding ecoregion factors (EFs) weighted according to their area within that MHT. These EFs can be calculated according to data specific to each ecoregion including species number, area of ecoregion, number of endemic species, and conservation status (from BIA, Lindner *et al.*, 2014). The sum of the area-weighted EFs then forms the HF of that MHT.

The biodiversity status (BS) is a function of an impact result for each of these midpoint impact categories. This is similar to the way endpoint categories are calculated in LCA. This BS depends on the parameter associated with the corresponding impact category, and the concerned region. BS = 0 means no biodiversity at all, and BS = 1 is the maximum state of biodiversity. It allows the practitioner to distinguish between impact severities on different regions. The impact functions are influenced by the given MHT and midpoint impact category.

The change in biodiversity is not the result of mass equivalents (units for midpoint category results) directly but of changes in, for example, concentration, pH, or temperature (units for impact functions). This means a unit conversion step is required to transfer midpoint LCIA results into useful units for the impact functions. This has to be done individually for each impact category. The example models the conversion given by Winter *et al.* (2018) include fate modelling (Suciu *et al.*, 2012) for the 'freshwater ecotoxicity' and 'freshwater eutrophication' impact categories. And the method from the Intergovernmental Panel on Climate Change report (IPCC; Stocker *et al.*, 2014) for the 'global warming' impact category.

4. Knowledge gaps biodiversity quantification

LCIA methodology is developing continuously. These four methods, IMPACT World+, LC-IMPACT, PBF, and BIA+, provide more sophisticated assessments for biodiversity loss than ReCiPe in 2016. However, assessment methods are used to best represent reality and are all plagued by one or more limitations or knowledge gaps (Winter *et al.*, 2018). This makes it interesting to analyse how four main LCIA knowledge gaps ('species diversity', ' spatial resolution', 'drivers', and 'trade-off') are addressed by these five methods. Each knowledge gap is assessed separately in this section, and an overview of how the knowledge gaps are addressed in each method is presented at the end.

4.1. Species diversity

Species diversity remains a problem in LCIA methodology because the loss of species richness does not capture the full aspect of biodiversity impact. Species richness is only one part of species diversity because species diversity is defined as the relation is species richness and evenness (Zhang *et al.*, 2012). Thus, species diversity is not only about the number of species (richness) but also about the abundance within these species (evenness). On top of this, biodiversity consists of more than species diversity solely. Biodiversity was defined on three levels by the UN in 1992: genetic diversity (within species), species diversity (between species), and ecosystem diversity (between ecosystems) (UN, 1992). This means measuring species richness of a taxonomic group does not necessarily include the other components of biodiversity (Winter *et al.*, 2018). It is important to keep this differentiation between species richness and biodiversity during the development of LCIA methods.

IMPACT World+ and LC-IMPACT hold on to the potential loss of species richness (in PDF) as metric for biodiversity loss. However, PDF is not properly adequate for several reasons. In most methods, PDF is estimated for vertebrates only, which is problematic as vertebrates only represent 2% of species worldwide (Crenna *et al.*, 2019). It also excludes species evenness, community composition, and distribution of species (Mace *et al.*, 2014; Winter *et al.*, 2018). The representative species can be chosen for each impact pathway individually. This results in different taxonomic coverage of biodiversity loss for the 'land use' impact category. In Chaudhary *et al.* (2015) mammals, birds, amphibians, and reptiles are addressed, while Jeanneret *et al.* (2008) even managed to include insects such as spiders, butterflies, and bees. It remains difficult to link the selected species groups to EU statistics (Crenna *et al.*, 2019). A more promising solution to represent actual biodiversity is to use the population trends for common birds and grassland butterflies as key indicators for biodiversity loss (EEA, 2018).

In the BIA+ method, another approach is presented to include the full coverage of biodiversity. The method defines biodiversity as an abstract concept which allows the practitioner to include all three levels of biodiversity. The biodiversity quantification with the biodiversity status (BS) accounts for the biodiversity condition in a specific region. An important benefit of this method is the prevention of double counting because the three biodiversity levels are assessed in general.

4.2. Spatial resolution assessment vs data

Also, the development of spatial resolution in the methods comes with its own balancing between the assessment level and data availability. Spatialisation in biodiversity impact is crucial, as a species going extinct in a region does not automatically mean extinction on a global level. Thus, global loss of species is irreversible while regional loss is not (de Baan *et al.*, 2015; Kuipers *et al.*, 2019). This means both levels of assessments are needed in order to give a complete view on the impact on biodiversity. If more specific taxa or surrogate species are used to increase the coverage of biodiversity impacts, regionalisation of impact assessments is required. As a consequence, the high resolution impact assessment model also requires a high resolution inventory database. Development of high resolution databases for LCA is lagging because of the lack of time and high costs for this data generation (Penman *et al.*, 2010). In combination with the fact that data are usually related to countries and not specific regions, the application of these high resolution methods is limited (Winter *et al.*, 2018).

ReCiPe2016, IMPACT World+, and LC-IMPACT are all spatialised methods. However, the most important impact pathways for biodiversity ‘land occupation’ and ‘land transformation’ in the AoP ‘ecosystem quality' are not spatialised in ReCiPe0216 yet (Asselin *et al.*, 2020). Since the midpoint impact categories are not included in LC-IMPACT yet, there is a need for further development of regionalised midpoint indicators and including the spatial dilemma these could cause to the endpoints (Verones *et al.*, 2020). The definition of species loss on different scales in these methods could be improved by taking species distribution on local, regional, and global scale (Woods *et al.*, 2017) and by integrating essential ecological aspects (Crenna *et al.*, 2019). Ecological aspects to be integrated include species vulnerability indicated by the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2022) and the spatial-explicitness of biodiversity impacts.

In BIA+, the use of the MHTs account for spatial resolution (Winter *et al.*, 2018). In order to increase regionalisation of the BIA+ method, LCA inventory data and the factors (HF & BS) are calculated on a country level. This is achievable through the top-down regionalisation approach from Berger (2014). This method allows the practitioner to estimate the amount of a chosen impact on a country level. The life cycle of a product has to be divided in production steps. These steps each have their own impact depending on production mixes, production sites, import-export shares, etc., allocated to specific countries. The production sites need to be well known for this method to work. If this is not the case, it is assumed the average production-mix shares given by different sources reflect the real environment (Winter *et al.*, 2018).

4.3. Drivers for biodiversity loss

It is difficult to capture all pressures influencing biodiversity loss. In 2010, the Secretariat of the Convention on Biological Diversity (SCBD) stated five drivers contributing to the loss of biodiversity: 1) habitat change, 2) climate change, 3) pollution, 4) overexploitation and unsustainable use, and 5) invasive species (SCBD, 2010). 'Habitat change is imperfectly included through the impact categories 'land use' and 'water use' (Winter *et al.*, 2018). The 'climate change' driver is captured through the 'global warming' or 'climate change' impact categories. 'Pollution' is partly included through impact categories such as 'acidification' and 'ecotoxicity'. With regard to biodiversity impacts, 'land use' is considered the most relevant impact category for biodiversity loss (MEA, 2005; Barnosky *et al.*, 2011; Winter *et al.*, 2018). LCA can be used to translate these man-made drivers into potential impacts on biodiversity. However, the few impact assessment methods available have a hard time covering all these five drivers, resulting in the methods mainly calculating the impacts on biodiversity for three of the five drivers (Curran *et al.*, 2011).

The impact driver 'habitat change' is included in ReCiPe2016, IMPACT World+, and LC-IMPACT but with slight differences. For 'habitat change', ReCiPe2016 and IMPACT World+ include 'land use' and 'water use' for both terrestrial and freshwater ecosystems (Tab. 1). LC-IMPACT includes 'land use' and 'water use' only for terrestrial ecosystems. 'Climate change' is an endpoint impact category in all three frameworks. 'Pollution' is indirectly included through 'acidification' and 'ecotoxicity' for terrestrial ecosystems, and through 'eutrophication' and 'ecotoxicity' for both freshwater and marine ecosystems in all three methods. 'Acidification' for freshwater ecosystems is also included in ReCiPe2016 and IMPACT World+, not in LC-IMPACT. The 'photochemical ozone formation' damage pathway to 'ecosystem quality' is included in ReCiPe2016 and LC-IMPACT, not in IMPACT World+. The SCBD drivers 'overexploitation and unsustainable use of biological resources' and 'invasive species' are not integrated in either of the three models. Also, IMPACT World+ comes with its limitations. In the midpoint categories, 23 additional impact categories are considered but are still too immature to be included in the method. These impact categories were provided as interim for sensitivity analysis only (Bulle *et al.*, 2019). Other impact categories such as photochemical oxidants' effect on vegetation, 'noise impact' and 'biotic resource use' are not included at all and should be developed for inclusion in the future. This means ReCiPe2016, IMPACT World+, and LC-IMPACT all cover only three of the five biodiversity impact drivers.

Table 1. Endpoint impact categories for ReCiPe2016, IMPACT World+, and LC-IMPACT for damage on the 'ecosystem quality' area of protection (AoP). 'Ecosystem quality' is divided in three ecosystem types (terrestrial, freshwater, and marine). The impact categories, for which ecosystem type was not specified, are listed as general for ecosystem. Immature impact categories in IMPACT World+ are shown as interim in italics. 'Ecosystem quality' impact categories were derived from Huijbregts *et al.* (2017), Bulle *et al.* (2019), and Verones *et al.* (2020).

Ecosystem type	ReCiPe2016	IMPACT World+	LC-IMPACT
General for ecosystems	-	Climate change	-
	-	Ionising radiation	-
	-	Thermally polluted water	-
	-	*Water stream use and management (interim)*	-
Terrestrial	Climate change	-	Climate change
	Photochemical ozone formation	-	Photochemical ozone formation
	Acidification	Acidification	Acidification
	Ecotoxicity	*Ecotoxicity (interim)*	Ecotoxicity
	Water use/stress	Water stress	Water stress
	Land use (transformation/occupation)	Land transformation, biodiversity	Land use
	-	Land occupation, biodiversity	-
	Land relaxation	-	-
Freshwater	Climate change	-	Climate change
	Acidification	Acidification	-
	Eutrophication	Eutrophication	Eutrophication
	Ecotoxicity	Ecotoxicity	Ecotoxicity
	Water stress	Water stress	-
Marine	-	Acidification	-
	Eutrophication	Eutrophication	Eutrophication
	Ecotoxicity	*Ecotoxicity (interim)*	Ecotoxicity

Crenna *et al.* (2019) concluded the main missing driver not covered by the LCA impact categories is 'invasive species'. This driver is linked to agricultural practises and international trade (EC, 2017) and data for these activities is still a field of research development. They also note some aspects are not included in the assessments yet, such as some pressures (such as overexploitation of biotic resources), some compartments or habitats (such as seafloor impacts), and some species (such as pollinators). Recommended impact categories to incorporate in the LC-IMPACT in the future would be 'noise', 'invasive species', 'salinisation', 'plastics', 'ocean acidification', specific 'ocean climate change', and different pollutants and toxicants (Verones *et al.*, 2020).

The BIA+ method is designed to capture the many parameters influencing biodiversity. Therefore, all existing LCA midpoint impact categories can be used in the BIA+ methodology as parameters (for calculation of the BS). It also aids practical use within LCA studies. This enables practitioners to calculate impacts of different pressures and of different drivers (Winter *et al.*, 2018). Although all SCBD drivers could be covered with the BIA+ method, this method is only available for case studies and not fully operational in an LCA framework yet (Crenna *et al.*, 2019). The PBF method is especially designed to cover all five SCBD drivers through its three-module framework (Asselin *et al.*, 2020). The three commonly-covered drivers are covered with the same endpoint approach as LC-IMPACT, and the two remaining drivers are given quality scores through semi-quantitative indicators. Although some extra indicators are added for 'habitat change' in the second module of PBF, other indicators are still missing, such as competition with threatened species, and destruction of species of socio-cultural value (Asselin *et al.*, 2020). Additional impact drivers to be added in LCAs are 'noise', 'artificial lights', and 'thermal pollution' (Winter *et al.*, 2017). Since there are still numerous indicators to be included, the need for continuous refinement of LCA methodology is stressed.

A possible step to take biodiversity assessments to the next level would be to also include the positive impacts on biodiversity. Most methods focus on biodiversity loss through damage to 'ecosystem quality'. It would be interesting to incorporate the positive effects. Asselin *et al.* (2020) does mention the potential to include positive impacts on biodiversity in the PBF method, but does not elaborate on this any further.

4.4. Trade-off LCA and biology

When combining biology research and LCA frameworks, trade-offs have to be made. Where a biologist would like to have a high resolution of biodiversity on a specific location, the LCA practitioner would try to evaluate environmental impacts on a global scale. It remains challenging to measure biodiversity exactly, as the measurements depend strongly on the perspective (Winter *et al.*, 2018). In ReCiPe2016, the LCA practitioner calculates environmental profiles at midpoint or endpoint level, depending on the scope of the LCA study. The combination of these levels in one method allows the practitioner to take advantage of either lower model uncertainty or higher environmental relevance, respectively (Bulle *et al.*, 2019). Nevertheless, the methods provide some solutions to deal with low biological data availability.

ReCiPe2016 represents different uncertainties and methodological choices in three different scenarios. This allows for relative comparisons when actual data is lacking. All scenarios need to be included in the assessment to create a sensitivity check of the LCA results. An important choice defining the scenarios is the time horizon for long-living pollutants (Huijbregts *et al.*, 2017). ReCiPe2016 uses three cultural perspectives to select the timeframe subjectively. For the individualist perspective, a 20-year time frame is used, assuming a short time frame. For the hierarchical perspective, a 100-year time frame is mostly used, as this perspective seeks consensus. For the egalitarian perspective, a 500-year time frame is used as a long term perspective. In this way, damaging effects in and balance of short and long term can be evaluated. It is to be noted this choice does not always influence all CFs of an impact category. Since the framework includes both mid- and endpoint categories, endpoint CFs (CF_{end}s) can be obtained from midpoint CFs (CF_{mid}s) through the use of a constant mid-to-endpoint factor per impact category (Huijbregts *et al.*, 2017). Nevertheless, the ReCiPe2016 LCIA method can still be further developed. Because of the lack of data, the influence of time horizon and level of evidence could not be included to calculate CFs for ‘photochemical ozone formation’, ‘terrestrial acidification’, ‘freshwater eutrophication’, and ‘land use’ (Huijbregts *et al.*, 2017). There is also major potential to improve the way the impact categories are modelled (Huijbregts *et al.*, 2017). On top of this, regionalisation of even more impact categories and their CFs is needed, more impact pathways need to be added, and species extinction should move from local to global (Huijbregts *et al.*, 2017).

LC-IMPACT includes the level of evidence for data through four sets of CFs to be used in four scenarios. When only certain impacts are selected, the model and parameter uncertainty is low and parts with high uncertainty are excluded. When all impacts are included, also the impacts with lower data availability are included. Inclusion of the two most extreme scenarios, ‘all impacts-long term’ and ‘certain impacts - 100 year’, is recommended as a minimum in an LCA study (Verones *et al.*, 2020). On top of this, LC-IMPACT discusses uncertainty in a qualitative way for all impact categories. Uncertainty increases when knowledge of exact impact mechanisms is limited, population levels and susceptibility are considered, or compartments for fate modelling are limited (Verones *et al.*, 2020). The inclusion of four CFs sets makes value choice more explicit and allows a mix of value choices if needed.

When data availability is limited, the source of the data becomes more important. PBF is especially designed to combine the top-down approach of LCA and the bottom-up approach of ecology (Asselin *et al.*, 2020). It forms a connection between the potential damage assessment by LCA and the actual observed damage in ecology. PBF can be used to assess impacts on biodiversity with a biodiversity score when data availability does not allow for calculation of biodiversity loss in percentage. It includes a priority order which allows the practitioner to select for as similar sources of data as possible (Tab. 2). If it is not possible to use the same data source for reference situation and product variant, the priority order table should be considered to use the most similar sources. In this way, ecology knowledge can be used to complement and refine LCA approaches, with a special focus on the consistency of source data.

Table 2. Priority order for data sources for biodiversity impact assessment of different variants of products. NGO = non-government organisation. This priority order can be used as a guideline to use data sources similar or as similar as possible. Derived from Asselin *et al.* (2020).

Priority order	Type of data source	Geographical scope of project	Species
1	Peer-reviewed	Specific area	All
2	Peer-reviewed	Specific area	Species the most impacted by the type of product or representative of the whole ecosystem state
3	Peer-reviewed	Ecoregion/country area	All
4	Peer-reviewed	Ecoregion/country area	Species the most impacted by the type of product or representative of the whole ecosystem state
5	Local NGO or company data	Specific area	All
6	Local NGO or company data	Specific area	Species the most impacted by the type of product or representative of the whole ecosystem state
7	Local NGO or company data	Ecoregion/country area	All
8	Local NGO or company data	Ecoregion/country area	Species the most impacted by the type of product or representative of the whole ecosystem state
9	Expert opinion	Specific area	All
10	Expert opinion	Specific area	Species the most impacted by the type of product or representative of the whole ecosystem state
11	Expert opinion	Ecoregion/country area	All
12	Expert opinion	Ecoregion/country area	Species the most impacted by the type of product or representative of the whole ecosystem state

The use of MHTs for calculating the habitat factor (HF) in BIA+ also comes with the assumption of equal biodiversity within an MHT. This is based on the MHT definition by the WWF which states that MHTs “share similar environmental conditions, habitat structure, and patterns of biological complexity, and that contain similar communities and species adaptations” (WWF, 2022). However, BIA+ does attempt to make this average for an MHT as reliable as possible because of the area-weighted ecoregions used in the HF calculation. This assumption is necessary in order to develop an applicable approach which is still useful for assessment purposes.

Also in BIA+, the data for the impact functions to calculate the biodiversity status is not readily available. Therefore, BIA+ uses expert judgements to base the impact functions per MHT and per impact category on. BIA+ is not the first method to rely on expert input because Penman *et al.* (2010), Lindner *et al.* (2014), and Lindqvist *et al.* (2016) have also suggested this approach before. A series of personal interviews with the prescribed questionnaire allows for the results to reflect the reality as well as possible. The experts should have scientific expertise within the area of ecosystem or biodiversity research. They should also have knowledge of specific conditions in the considered area, about the considered parameter and the respective MHT, and of existing classification, limitations, etc., for different parameters (Winter *et al.*, 2018). It is likely a group of experts is desirable to fulfil all these requirements and to obtain the most accurate results. It should be noted that it is crucial to keep this process transparent: which experts have been interviewed, when, where, and how. The experts will first form a qualitative judgement for the impact categories, followed by a quantitative judgement to obtain values for the impact functions. The use of expert judgements should result in a well-reviewed, likely case specific, compromise between biology and LCA.

4.5. Conclusion

As with all LCIA methods, ReCiPe2016, IMPACT World+, LC-IMPACT, PBF, and BIA+ provide a simplified representation of the environmental mechanisms. The combination of modelling choices and the limited knowledge of environmental sciences are reoccurring challenges for LCA methodology. Nevertheless, quantification of biodiversity in LCA methodology has shown promising developments over the last few years. An overview of the developments in the assessed methods can be seen in Table 3. Species richness remains the most useable representation of biodiversity, although effort is made to present biodiversity as an abstract concept to include genetic and ecosystem diversity. As more data becomes available, the spatial resolution of LCA assessments can increase. On top of this, inclusion of all five drivers for biodiversity loss is becoming a possibility. Lastly, most methods present a way for weighted choices regarding the trade-off between biology research and LCA frameworks. Besides fine-tuning the already available assessment methods, it would be valuable to include ecosystem services in LCA frameworks in the future. Since current LCA methodology focuses strongly on biodiversity loss, future research is required to allow implementation of positive impacts on biodiversity in LCA frameworks. To conclude, LCIA results should always be interpreted with care, with acknowledgement for the underlying modelling choices, hypotheses, and limitations.

Table 3. Overview of how the knowledge gaps for biodiversity quantification were addressed by the assessed methods. Promising developments can be seen for biodiversity quantification over the last few years. PDF = potential disappeared fraction, CFs = characterisation factors.

Knowledge gap	**ReCiPe2016** (Huijbregts *et al.*, 2017)	**IMPACT World+** (Bulle *et al.*,2019)	**LC-IMPACT** (Verones *et al.*,2020)	**PBF** (Asselin *et al.*, 2020)	**BIA+** (Winter *et al.*, 2018)
Species diversity	Species richness in PDF	Species richness in PDF	Species richness in global PDF	Species richness in global PDF	Species, genetic, and ecosystem diversity; biodiversity abstract concept
Spatial resolution assessment vs data	CFs at four scales; ‘land occupation’ and ‘land transformation’ not spatialised	CFs at four scales	CFs at four scales; regionalised midpoint indicators to be developed	Similar to LC-IMPACT; country level core CFs	Use MHTs
SCBD drivers	3/5: habitat change, climate change, pollution	3/5: habitat change, climate change, pollution	3/5: habitat change, climate change, pollution	5/5: habitat change, climate change, pollution, overexploitation, invasive species	5/5: habitat change, climate change, pollution, overexploitation, invasive species
Trade-off LCA and biology	Combine mid- and endpoint; cultural perspectives	-	Four sets of CFs for four scenarios	Priority order for data source	Qualitative and quantitative expert judgements

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6. Supplementary table

Table S1. References for timeline overview of articles and methods related to life cycle impact assessment (LCIA) frameworks considering biodiversity. Articles are sorted by year (see first column). The title and objective of each study are derived from the corresponding reference. Table is adapted after Gabel *et al.* (2016) and extended with articles from literature research.

	Article	Title	Objective of study	Full reference
1999	Eco-Indicator 99 - Goedkoop (1999)	The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment	Present Eco-Indicator 99 methodology.	Goedkoop, M. (1999): The Eco-indicator 99 - A damage oriented method for Life Cycle Impact Assessment. Methodology Report. Second edition 17-4-2000. PRé Consultants B.V., Amersfoort, The Netherlands
2000	EDIP - Hauschild & Potting (2000)	Guidelines on spatial differentiation in life cycle impact assessment–the EDIP2000 methodology	Present the EDIP2000 method.	Hauschild, M., & Potting, J. (2001). Guidelines on spatial differentiation in life cycle impact assessment–the EDIP2000 methodology. Final draft. Institute for Product Development, Technical University of Denmark (manuscript).
	Lindeijder (2000)	Biodiversity and life support impacts of land use	Include the main impacts of land use on ecosystems in LCAs, under commission of the Dutch Ministry of Transport, Public Works and Water Management.	Lindeijer, E. (2000). Biodiversity and life support impacts of land use in LCA. Journal of Cleaner Production, 8(4), 313-319.
2002	Brentrup *et al.* (2002)	Life cycle impact assessment of land use based on the hemeroby concept	Present an approach which enables an analysis of the degree of human influence on an area due to different types of land use.	Brentrup, F., Küsters, J., Lammel, J., & Kuhlmann, H. (2002). Life cycle impact assessment of land use based on the hemeroby concept. The International Journal of Life Cycle Assessment, 7(6), 339-348.
	CML - Guinée & Lindeijer (2002)	Handbook on life cycle assessment: operational guide to the ISO standards	Guide to standards that give advice about the performance of LCA.	Guinée, J. B., & Lindeijer, E. (Eds.). (2002). Handbook on life cycle assessment: operational guide to the ISO standards (Vol. 7). Springer Science & Business Media.
	Haes *et al.* (2002)	UNEP/SETAC life cycle initiative: background, aims and scope	Development of the content of the LC Initiative.	Haes, H., Jolliet, O., Norris, G., & Saur, K. (2002). UNEP/SETAC life cycle initiative: background, aims and scope. The International Journal of Life Cycle Assessment, 7(4), 192-195.
	Schenck (2002)	Land use and biodiversity indicators for life cycle impact assessment.	Describes the beginnings of an effort jointly sponsored by the Defenders of Wildlife and the Institute for Environmental Research and Education.	Schenck, R. C. (2001). Land use and biodiversity indicators for life cycle impact assessment. The International Journal of Life Cycle Assessment, 6(2), 114-117.

2003	IMPACT2002+ - Jolliet *et al.* (2003)	IMPACT 2002+: a new life cycle impact assessment methodology	Discuss the main assessment characteristics for midpoint and damage categories, as well as related normalisation factors, with a focus on innovative features and performed adaptations.	Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: a new life cycle impact assessment methodology. The international journal of life cycle assessment, 8(6), 324-330.
2004	Jolliet *et al.* (2004)	The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative	Present the main features of the framework proposed in the LCIA definition study, and develops it further to ensure a consistent description of midpoint and damage categories.	Jolliet, O., Müller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R. & Weidema, B. (2004). The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. The International Journal of Life Cycle Assessment, 9(6), 394-404.
2005	Kyläkorpi *et al.* (2005)	The Biotope Method 2005 a Method to Assess the Impact of Land Use on Biodiversity	Present the Biotope Method 2005 methodology.	Kyläkorpi, K., Rydgren, B., Ellegård, A., Miliander, S., & Grusell, E. (2005). The Biotope Method 2005: a method to assess the impact of land use on biodiversity. Vattenfall, Sweden.
	LUCAS - Toffoletto *et al.* (2007)	LUCAS-A new LCIA method used for a Canadian-specific context	Present the characterization models selected for LUCAS.	Toffoletto, L., Bulle, C., Godin, J., Reid, C., & Deschênes, L. (2007). LUCAS-A new LCIA method used for a Canadian-specific context. The International Journal of Life Cycle Assessment, 12(2), 93-102.
2007	Scholz (2007)	Assessment of land use impacts on the natural environment. Part 1: an analytical framework for pure land occupation and land use change.	Contribute to that discussion by providing a consistent methodological framework for the assessment of land occupation and transformation.	Scholz, R. (2007). Assessment of land use impacts on the natural environment. Part 1: an analytical framework for pure land occupation and land use change (8 pp). The International Journal of Life Cycle Assessment, 12(1), 16-23.
	Burke *et al.* (2008)	Testing a Scandinavian biodiversity assessment tool in an African desert environment	Test the applicability of a Scandinavian biodiversity assessment tool, developed specifically for use with EPD applications, in an African desert environment, linking the industry types power generation and mining.	Burke, A., Kyläkorpi, L., Rydgren, B., & Schneeweiss, R. (2008). Testing a Scandinavian biodiversity assessment tool in an African desert environment. Environmental management, 42(4), 698-706.
	Koellner & Scholz (2008)	Assessment of land use impacts on the natural environment. Part 2 : generic characterization factors for local species diversity in Central Europe.	Develop generic characterization factors for land use types using empirical information on species diversity from Central Europe, which can be used in the assessment method developed in the first part of this series of paper.	Koellner, T., & Scholz, R. W. (2008). Assessment of land use impacts on the natural environment. The International Journal of Life Cycle Assessment, 13(1), 32-48.
	Michelsen (2008)	Assessment of land use impact on biodiversity	Presents a new methodology for how land use impacts on biodiversity can be included in LCA.	Michelsen, O. (2008). Assessment of land use impact on biodiversity. The International Journal of Life Cycle Assessment, 13(1), 22-31.

2008

	Rosenbaum *et al.* (2008)	USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment.	1. identify specific sources of differences between the models' results and structure, 2. detect the indispensable model components, and 3. build a scientific consensus model from them, representing recommended practice.	Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, M. A., Jolliet, O., Juraske, R. & Hauschild, M. Z. (2008). USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. The International Journal of Life Cycle Assessment, 13(7), 532-546.
	Schmidt (2008)	Development of LCIA characterisation factors for land use impacts on biodiversity. J.	Provide a platform from which common problems can be incorporated in LCA.	Schmidt, J. H. (2008). Development of LCIA characterisation factors for land use impacts on biodiversity. Journal of Cleaner Production, 16(18), 1929-1942.
2009	LC-IMPACT - Friedrich *et al.* (2009)	Development and application of environmental Life Cycle Impact assessment Methods for improved sustainability Characterisation of Technologies	Present LC-IMPACT methodology.	Friedrich, R., Kounina, A., Humbert, S., Jolliet, O., Preiss, P., Roos, J., & Torras, S. (2009) Project number: 243827 FP7-ENV-2009-1 Project acronym: LC-IMPACT Project title: Development and application of environmental Life Cycle Impact assessment Methods for improved sustainability Characterisation of Technologies.
	ReCiPe2008 - Goedkoop *et al.* (2009)	ReCiPe 2008. A Life Cycle Impact Assessment Method, Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level	Describe the implementation of a method that is harmonised with respect to modelling principles and choices, but which offers results at both the midpoint and endpoint levels.	Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1, 1-126.
2010	Geyer *et al.* (2010)	Coupling GIS and LCA for biodiversity assessment of land use Part 1: inventory modelling and Part 2: impact assessment	Present a proof-of-concept approach for coupling GIS and LCA for biodiversity assessments of land use and applies it to a case study of ethanol production from agricultural crops in California.	Geyer, R., Lindner, J. P., Stoms, D. M., Davis, F. W., & Wittstock, B. (2010). Coupling GIS and LCA for biodiversity assessments of land use: Part 1: inventory modeling and Part 2: Impact assessment. The International Journal of Life Cycle Assessment, 15(7).
	Penman *et al.* (2010)	A proposal for accounting for biodiversity in life cycle assessment	Propose an alternative approach for the incorporation of a biodiversity score into LCA that can be realistically achieved in the foreseeable future.	Penman, T. D., Law, B. S., & Ximenes, F. (2010). A proposal for accounting for biodiversity in life cycle assessment. Biodiversity and Conservation, 19(11), 3245-3254.
2012	IMPACT World+ - Bulle *et al.* (2012)	IMPACT World+: a new global regionalized life cycle impact assessment method	Present IMPACT World+ methodology	Bulle, C., Jolliet, O., Humbert, S., Rosenbaum, R., & Margni, M. (2012). IMPACT World+: a new global regionalized life cycle impact assessment method. LCA XII, United States, Washington, Tacoma.
	Urban (2012)	Spatially differentiated examination of biodiversity in LCA (Life Cycle Assessment) on national scale, exemplified by biofuels.	Propose a methodological approach for accounting the impact of different biofuel targets on biodiversity (Section 2), as well as its operationalization with indicators based on nationally available data in Germany, and then test this approach (Section 3)	Urban, B. (2012). Spatially differentiated examination of biodiversity in LCA (Life Cycle Assessment) on national scale, exemplified by biofuels.

	De Baan *et al.* (2013a)	Land use impacts on biodiversity in LCA: a global approach	Propose a first approach to quantify biodiversity impacts in LCIA in different world regions based on empirical data, focusing on the facet of species composition.	De Baan, L., Alkemade, R., & Koellner, T. (2013). Land use impacts on biodiversity in LCA: a global approach. The International Journal of Life Cycle Assessment, 18(6), 1216-1230.
	De Baan *et al.* (2013b)	Land use in life cycle assessment: global characterisation factors based on regional and global potential species extinction	Present a spatially explicit approach to assess the impacts of land use on biodiversity at both regional and global scales.	De Baan, L., Mutel, C. L., Curran, M., Hellweg, S., & Koellner, T. (2013). Land use in life cycle assessment: global characterisation factors based on regional and global potential species extinction. Environmental science & technology, 47(16), 9281-9290.
	De Schryver & Goedkoop (2013)	Chapter 10: Impacts of land use	Reflect the damage to ecosystems due to the effects of occupation and transformation of land.	Chapter 10: Impacts of land use. De Schryver, A., Goedkoop, M. (2013) In: Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1, 1-126.
	De Souza *et al.* (2013)	Land use impacts on biodiversity in LCA: proposal of characterisation factors based on functional diversity	1. Use an FD index covering several taxonomic levels for the calculation of characterisation factors for land use impacts on biodiversity in LCIA. 2. Evaluate its influence on biodiversity characterisation factors compared with current practice. 3. Assess how far increased complexity and data requirements of the new biodiversity indicator are justified by improved completeness, reliability, and environmental relevance.	De Souza, D. M., Flynn, D. F., DeClerck, F., Rosenbaum, R. K., de Melo Lisboa, H., & Koellner, T. (2013). Land use impacts on biodiversity in LCA: proposal of characterisation factors based on functional diversity. The International Journal of Life Cycle Assessment, 18(6), 1231-1242.
	Koellner *et al.* (2013)	UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA	Move beyond the description of key elements by suggesting specific guidelines for a comprehensive and consistent impact assessment encompassing all pathways that originate from land use and damages to biodiversity and ecosystem services.	Koellner, T., De Baan, L., Beck, T., Brandão, M., Civit, B., Margni, M. & Müller-Wenk, R. (2013). UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. The International Journal of Life Cycle Assessment, 18(6), 1188-1202.
2013	Muller *et al.* (2013)	Assessment of environmental effects, animal welfare and milk quality among organic dairy farms	Systemic comparison of different dairy farm types within the organic dairy sector in Germany, considering intra-farm interactions and all relevant environmental impact categories.	Müller-Lindenlauf, M., Deittert, C., & Köpke, U. (2010). Assessment of environmental effects, animal welfare and milk quality among organic dairy farms. Livestock Science, 128(1-3), 140-148.
2014	BIA - Lindner *et al.* (2014)	Proposal of a unified biodiversity impact assessment method	Generate product-related biodiversity impact information and manage biodiversity along value chains.	Lindner, J. P., Niblick, B., Eberle, U., Bos, U., Schmincke, E., Schwarz, S. & Urbanek, A. (2014, October). Proposal of a unified biodiversity impact assessment method. In 9th International Conference, LCA of Food (Vol. 8, No. 10).

	Coelho & Michelsen (2014)	Land use impacts on biodiversity from kiwifruit production in New Zealand assessed with global and national datasets	Present a model that enables assessments of land use impacts on biodiversity in life cycle impact assessment (LCIA), independent of any particular biogeographic region, based on globally available data with a higher resolution than biomes.	V Coelho, C. R., & Michelsen, O. (2014). Land use impacts on biodiversity from kiwifruit production in New Zealand assessed with global and national datasets. The International Journal of Life Cycle Assessment, 19(2), 285-296.
	Jeanneret *et al.* (2014)	An expert system for integrating biodiversity into agricultural life-cycle assessment	Present an expert system to estimate and compare the impact of farming systems on biodiversity using a set of indicator-species groups. In a case study	Jeanneret, P., Baumgartner, D. U., Knuchel, R. F., Koch, B., & Gaillard, G. (2014). An expert system for integrating biodiversity into agricultural life-cycle assessment. Ecological Indicators, 46, 224-231.
	Saling *et al.* (2014)	Assessment of biodiversity within the holistic sustainability evaluation method of AgBalance	Discussion of the results and implications of applying the biodiversity indicator set of AgBalance.	Saling, P., Schöneboom, J., Künast, C., Ufer, A., Gipmans, M., & Frank, M. (2014). Assessment of Biodiversity within the Holistic Sustainability Evaluation Method of AgBalance. In 9th International Conference, LCA of Food.
2015	Chaudhary *et al.* (2015)	Quantifying land use impacts on biodiversity: combining species-area models and vulnerability indicators.	Address four shortcomings of CFs and provide an updated impact assessment approach and characterisation factors for regional (CF regional) and global biodiversity loss (CF global) using the Countryside SAR.	Chaudhary, A., Verones, F., De Baan, L., & Hellweg, S. (2015). Quantifying land use impacts on biodiversity: combining species–area models and vulnerability indicators. Environmental science & technology, 49(16), 9987-9995.
	De Baan *et al.* (2015)	High-resolution assessment of land use impacts on biodiversity in life cycle assessment using species habitat suitability models.	Present a novel LCA land use assessment method that addresses some LCA shortcomings.	De Baan, L., Curran, M., Rondinini, C., Visconti, P., Hellweg, S., & Koellner, T. (2015). High-resolution assessment of land use impacts on biodiversity in life cycle assessment using species habitat suitability models. Environmental science & technology, 49(4), 2237-2244.
	Fehrenbach *et al.* (2015)	Hemeroby as an impact category indicator for the integration of land use into life cycle (impact) assessment	Review relevant methodology proposed to date with special reference to the hemeroby concept to identify a consistent method that captures the complexity of land use without oversimplification and loss of crucial information.	Fehrenbach, H., Grahl, B., Giegrich, J., & Busch, M. (2015). Hemeroby as an impact category indicator for the integration of land use into life cycle (impact) assessment. The International Journal of Life Cycle Assessment, 20(11), 1511-1527.
2016	Curran *et al.* (2016)	How Well Does LCA Model Land Use Impacts on Biodiversity? A Comparison with Approaches from Ecology and Conservation	Update the general modelling framework of Koellner *et al.* (2013), identify best-practice guidelines from existing models, assess how well LCA models stand up to those from outside the field, and provide recommendations on further development to fill conceptual gaps.	Curran, M., Maia de Souza, D., Antón, A., Teixeira, R. F., Michelsen, O., Vidal-Legaz, B. & Mila i Canals, L. (2016). How Well Does LCA Model Land Use Impacts on Biodiversity? A Comparison with Approaches from Ecology and Conservation. Environmental science & technology, 50(6), 2782-2795.
	Frischknecht *et al.* (2016)	National environmental footprints and planetary boundaries: from methodology to policy implementation, 59th LCA forum	Present the highlights of the 59th LCA forum held on 12 June 2015.	Frischknecht, R., Stolz, P., & Tschümperlin, L. (2016). National environmental footprints and planetary boundaries: from methodology to policy implementation 59th LCA forum, Swiss Federal Institute of Technology, Zürich, June 12, 2015. The International Journal of Life Cycle Assessment, 21(4), 601-605.

	Gabel *et al.* (2016)	The challenges of including impacts on biodiversity in agricultural life cycle assessments	Review existing impact assessment methods for biodiversity that are used in LCAs, and to evaluate their suitability for application in LCAs in agricultural contexts.	Gabel, V. M., Meier, M. S., Köpke, U., & Stolze, M. (2016). The challenges of including impacts on biodiversity in agricultural life cycle assessments. Journal of Environmental Management, 181, 249-260.
	Huijbregts *et al.* (2016)	ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level	Provides an overview of the key elements of the ReCiPe2016 method.	Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M. & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22(2), 138-147.
	LC-IMPACT - Verones *et al.* (2016)	LC-Impact Version 0.5: a spatially differentiated life cycle impact assessment approach.	Present LC-IMPACT methodology.	Verones, F., Hellweg, S., Azevedo, L. B., Chaudhary, A., Cosme, N., Fantke, P. & Huijbregts, M. A. J. (2016). LC-Impact Version 0.5: a spatially differentiated life cycle impact assessment approach. Advance Access published.
2017	Knudsen *et al.* (2017)	Characterization factors for land use impacts on biodiversity in life cycle assessment based on direct measures of plant species richness in European farmland in the 'Temperate Broadleaf and Mixed Forest' biome	Estimate occupation CFs for land use impacts on species richness for the biome 'Temperate Broadleaf and Mixed Forest', that are able to distinguish between different land use types and between organic and conventional farming practices.	Knudsen, M. T., Hermansen, J. E., Cederberg, C., Herzog, F., Vale, J., Jeanneret, P. & Dennis, P. (2017). Characterization factors for land use impacts on biodiversity in life cycle assessment based on direct measures of plant species richness in European farmland in the 'Temperate Broadleaf and Mixed Forest'biome. Science of the Total Environment, 580, 358-366.
	Marques *et al.* (2017)	How to quantify biodiversity footprints of consumption? A review of multi-regional input-output analysis and life cycle assessment	Review how environmentally extended multi-regional input–output analysis and life cycle assessment have been used to analyse the impacts of consumption on biodiversity, as well as the main challenges in doing so.	Marques, A., Verones, F., Kok, M. T., Huijbregts, M. A., & Pereira, H. M. (2017). How to quantify biodiversity footprints of consumption? A review of multi-regional input–output analysis and life cycle assessment. Current opinion in environmental sustainability, 29, 75-81.
	Verones *et al.* (2017)	LCIA framework and cross-cutting issues guidance within the UNEP-SETAC life cycle initiative	Deliver recommendations that are currently ready for consideration, and give an outlook where further research and harmonization are needed.	Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S. & Fantke, P. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. Journal of cleaner production, 161, 957-967.
	Winter *et al.* (2017)	Including biodiversity in life cycle assessment – State of the art, gaps, and research needs	Analyse how biodiversity is currently viewed in LCA, to highlight limitations and gaps and to provide recommendations for further research	Winter, L., Lehmann, A., Finogenova, N., & Finkbeiner, M. (2017). Including biodiversity in life cycle assessment–State of the art, gaps and research needs. Environmental Impact Assessment Review, 67, 88-100.
2018	Chaudhary & Brooks (2018)	Land Use Intensity-Specific Global Characterization Factors to Assess Product Biodiversity Footprints	Present first attempts toward addressing five improvements of CFs and calculate updated CFs for five broad land use types and their three intensity levels.	Chaudhary, A., & Brooks, T. M. (2018). Land use intensity-specific global characterization factors to assess product biodiversity footprints. Environmental Science & Technology, 52(9), 5094-5104.

	Gabel *et al.* (2018)	Evaluating On-Farm Biodiversity: A Comparison of Assessment Methods	Evaluate and compare a selection of biodiversity assessment methods by applying several methods to each of a set of case study farms	Gabel, V., Home, R., Stöckli, S., Meier, M., Stolze, M., & Köpke, U. (2018). Evaluating on-farm biodiversity: a comparison of assessment methods. Sustainability, 10(12), 4812.
	Jeswani *et al.*, (2018)	Accounting for land use, biodiversity, and ecosystem services in life cycle assessment: Impacts of breakfast cereals	Quantify the impact of land use on biodiversity and ecosystem services associated with the production of breakfast cereals.	Jeswani, H. K., Hellweg, S., & Azapagic, A. (2018). Accounting for land use, biodiversity, and ecosystem services in life cycle assessment: Impacts of breakfast cereals. Science of the Total Environment, 645, 51-59.
	Jolliet *et al.* (2018)	Global guidance on environmental life cycle impact assessment indicators: Impacts of climate change, fine particulate matter formation, water consumption and land use	Presents the consensus building process and scientific approach retained, as well as the indicators selected and recommendations reached for the above-described selected impact categories and cross-cutting issues	Jolliet, O., Antón, A., Boulay, A. M., Cherubini, F., Fantke, P., Levasseur, A. & Frischknecht, R. (2018). Global guidance on environmental life cycle impact assessment indicators: impacts of climate change, fine particulate matter formation, water consumption and land use. The International Journal of Life Cycle Assessment, 23(11), 2189-2207.
	Rossi *et al.* (2018)	Capturing the potential biodiversity effects of forestry practices in life cycle assessment	Develop a method, applicable to boreal forestry systems, capable of building the quantitative component (as mentioned above) of potential land occupation impacts of various forest management practices on biodiversity.	Rossi, V., Lehesvirta, T., Schenker, U., Lundquist, L., Koski, O., Gueye, S. & Humbert, S. (2018). Capturing the potential biodiversity effects of forestry practices in life cycle assessment. The International Journal of Life Cycle Assessment, 23(6), 1192-1200.
	Teixeira *et al.* (2018)	A Practical Comparison of Regionalized Land Use and Biodiversity Life Cycle Impact Assessment Models Using Livestock Production as a Case Study	Present a practical application study of LCIA models without any ex ante judgment of model assumptions and data or institutional support.	Teixeira, R. F., Morais, T. G., & Domingos, T. (2018). A practical comparison of regionalized land use and biodiversity life cycle impact assessment models using livestock production as a case study. Sustainability, 10(11), 4089.
	BIA+ - Winter *et al.* (2018)	Biodiversity Impact Assessment (BIA+) – Methodological Framework for Screening Biodiversity	Include further and often neglected environmental interferences and their impacts on biodiversity.	Winter, L., Pflugmacher, S., Berger, M., & Finkbeiner, M. (2018). Biodiversity impact assessment (BIA+)–methodological framework for screening biodiversity. Integrated Environmental Assessment and Management, 14(2), 282-297.
2019	IMPACT World+ - Bulle *et al. (2019)*	IMPACT World+: a globally regionalized life cycle impact assessment method	Provide an overview of the key elements of the IMPACT World+ method.	Bulle, C., Margni, M., Patouillard, L., Boulay, A. M., Bourgault, G., De Bruille, V. & Jolliet, O. (2019). IMPACT World+: a globally regionalized life cycle impact assessment method. The International Journal of Life Cycle Assessment, 24(9), 1653-1674.
	Crenna *et al.* (2019)	Biodiversity impacts due to food consumption in Europe	1. improve the work previously done by Notarnicola et al. (2017), expanding the environmental assessment from 19 to 32 representative food products; 2. evaluate the role of EU food consumption in the current biodiversity decline, presenting results of midpoint and endpoint modelling;	Crenna, E., Sinkko, T., & Sala, S. (2019). Biodiversity impacts due to food consumption in Europe. Journal of cleaner production, 227, 378-391.

			3. unveil biodiversity loss drivers currently not captured by LCA modelling, which should be addressed in future research.	
	Di Fulvio *et al.* (2019)	Spatially explicit LCA analysis of biodiversity losses due to different bioenergy policies in the European Union	Set out a global framework that is able to jointly assess and analyse the biodiversity implications of policies related to: direct land use change, changes in intensity in land use and forestry, and in-direct land use effects.	Di Fulvio, F., Forsell, N., Korosuo, A., Obersteiner, M., & Hellweg, S. (2019). Spatially explicit LCA analysis of biodiversity losses due to different bioenergy policies in the European Union. Science of the total environment, 651, 1505-1516.
	Lindner *et al.* (2019)	Valuing Biodiversity in Life Cycle Impact Assessment	Present a new method that allows the assessment of potential impacts of land-using production processes on biodiversity all over the world by integrating the concept of hemeroby into a mathematical framework.	Lindner, J. P., Fehrenbach, H., Winter, L., Bloemer, J., & Knuepffer, E. (2019). Valuing biodiversity in life cycle impact assessment. Sustainability, 11(20), 5628.
	Maier *et al.* (2019)	Conceptual Framework for Biodiversity Assessments in Global Value Chains	Describe a new methodological framework for biodiversity assessment in LCA that could close some research gaps, including the compilation and suggestion of suitable datasets. In the end, it discusses its advantages as well as its limitations	Maier, S. D., Lindner, J. P., & Francisco, J. (2019). Conceptual framework for biodiversity assessments in global value chains. Sustainability, 11(7), 1841.
	Vrasdonk *et al.* (2019)	Reference situations for biodiversity in life cycle assessments: conceptual bridging between LCA and conservation biology	Contribute to an improved methodology for assessing biodiversity impacts in LCA through developing the use of reference situations in life cycle impact assessment (LCIA) models of land use	Vrasdonk, E., Palme, U., & Lennartsson, T. (2019). Reference situations for biodiversity in life cycle assessments: conceptual bridging between LCA and conservation biology. The International Journal of Life Cycle Assessment, 24(9), 1631-1642.
2020	Asselin *et al.* (2020)	Product Biodiversity Footprint e A novel approach to compare the impact of products on biodiversity combining Life Cycle Assessment and Ecology	Present the PBF methodology and its application to the L'Oréal shower gel case study.	Asselin, A., Rabaud, S., Catalan, C., Leveque, B., L'Haridon, J., Martz, P., & Neveux, G. (2020). Product Biodiversity Footprint–A novel approach to compare the impact of products on biodiversity, combining Life Cycle Assessment and Ecology. Journal of Cleaner Production, 248, 119262.
	Gaudreault *et al.* (2020)	Are the factors recommended by UNEP-SETAC for evaluating biodiversity in LCA achieving their promises: a case study of corrugated boxes produced in the US	Apply the CFs for "Potential Species Loss" from Chaudhary *et al.* (2015) for hotspot analysis, and to identify potential improvement opportunities in the life cycle of corrugated boxes produced in the US	Gaudreault, C., Loehle, C., Prisley, S., Solarik, K. A., & Verschuyl, J. P. (2020). Are the factors recommended by UNEP-SETAC for evaluating biodiversity in LCA achieving their promises: a case study of corrugated boxes produced in the US. The International Journal of Life Cycle Assessment, 25(6), 1013-1026.
	LC-IMPACT - Verones *et al.* (2020)	LC-IMPACT: A regionalized life cycle damage assessment method	Provides an overview of the key elements of the LC-IMPACT method.	Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N. & Huijbregts, M. A. (2020). LC-IMPACT: A regionalized life cycle damage assessment method. Journal of Industrial Ecology, 24(6), 1201-1219.
2	Potter *et al.*	Multi-criteria evaluation of plant-based	Present a method for environmental multi-criteria evaluation of	Potter, H. K., & Röös, E. (2021). Multi-criteria evaluation of plant-based foods–use of environmental footprint and LCA data for consumer

0 2 1	(2021)	foods – use of environmental footprint and LCA data for consumer guidance	plant-based products to enable communication through a consumer guide, which was developed in cooperation with World Wide Fund for Nature (WWF) Sweden and involves a real-life case of implementation.	guidance. Journal of cleaner production, 280, 124721.