RENEWABLE
CARBON
INITIATIVE
REPORT

Biodiversity in Sustainability Assessments – in Particular Life-Cycle-Assessments (LCA)

RCI Background Report

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1 Executive summary

The chemical and materials industry is facing a fundamental transformation driven by environmental pressures, regulatory demands, feedstock security, and the need for long-term sustainability and resilience. A central challenge is reducing dependence on fossil-based feedstocks in order to lower greenhouse gas emissions and strengthen Europe's strategic autonomy. Alongside recycling and carbon capture and utilisation, biomass represents a key renewable carbon source for defossilising chemical and materials production. Recent studies estimate that around 20% of global biomass could be used in a net-zero bioeconomy by 2050, a target considered achievable through sustainable, moderately high-tech agricultural systems (Harrandt, Carus et al. 2024). However, expanding biomass use raises concerns about additional pressures on biodiversity and ecosystems, making careful management essential. Although the chemical and materials sector currently uses only a small share of global biomass – around 11% compared to food (15%), feed (56%), and bioenergy uses (16%) – the bioeconomy has the potential to become a frontrunner in biodiversity protection. This is due both to its responsibility to operate sustainably and to the availability of analytical tools to address climate and biodiversity impacts simultaneously. A key question is how sufficient biomass production can be ensured while safeguarding biodiversity.

Biodiversity is defined as the variability among living organisms and ecosystems, encompassing three interconnected levels: species diversity, genetic diversity within species, and ecosystem diversity and functionality. According to IPBES, biodiversity loss is driven by five main factors: land and sea-use change, climate change, direct exploitation of organisms, invasive alien species, and pollution. These drivers are influenced by numerous pressures, such as land and water use, greenhouse gas emissions, and fertilizer application. While some drivers can be quantified through existing LCA impact categories, such as climate change or land use, there is currently no scientific consensus on biodiversity metrics or assessment methodologies, limiting their integration into business decision-making.

This report is the second of three interconnected parts addressing this challenge. Part one provides an overview of the drivers and consequences of biodiversity loss, relevant global and European policies, and trade-offs between biomass production and biodiversity conservation. Part two, the focus of this report, aims to transparently present current approaches to assessing biodiversity impacts in terrestrial Life Cycle Assessment (LCA), discuss their applicability, and identify open research questions. Part three explores agricultural and forestry measures that can protect or enhance biodiversity without compromising biomass yields, supported by global case studies.

Within this report, biodiversity-related LCIA methods are reviewed, which were developed over the last decade, including ReCiPe2016, IMPACT World+, LC-IMPACT, Product Biodiversity Footprint (PBF), Biodiversity Impact Assessment+ (BIA+), BioMAPS, Global Extinction Potential (GEP), UNEP-GLAM, and Biodiversity Value Increment (BVI). These methods are evaluated according to their integration of biodiversity levels and drivers, data and regionalisation approaches, applicability in practice (including software availability), and general methodological aspects. A particular focus is placed on land use, as it is a common indicator across all reviewed methods and allows direct comparison.

A key finding is that no single method simultaneously covers all three biodiversity levels (ecosystem, species, genetic) and all five major drivers of biodiversity loss (climate change, habitat loss, pollution, overexploitation, invasive species). Methods can be divided into single-indicator and multi-indicator approaches. Single-indicator methods, such as BIA+, BVI, and BioMAPS, mainly focus on land use and are therefore limited in their coverage of drivers. Multi-indicator methods, including ReCiPe2016, LC-IMPACT, IMPACT World+, UNEP-GLAM, and GEP, address land use, climate change, and pollution, and consider additional pressures relevant to biodiversity, but generally exclude invasive species, overexploitation, and genetic or ecosystem-level impacts. PBF stands out as the approach aims to address all five drivers, though it primariliy focusses on species biodiversity and relies partly on semi-quantitative (non-LCA) assessments.

In terms of applicability, ReCiPe, LC-IMPACT, IMPACT World+, and UNEP-GLAM are publicly usable, with the first three already integrated into LCA software. UNEP-GLAM is expected to be integrated into SimaPro by 2026. BioMAPS, developed as a land-use-focused indicator, is proposed for inclusion in the upcoming Environmental Footprint (EF) method, anticipated around 2026.

All assessed methods were developed within the last ten years and either build on each other, incorporate some aspects of each other or use the same/similar data sources. GLAM and BioMaps are the most recent methods and include methodological aswell as data aspects/sources from former methods. BioMaps focuses on land use aspects only, as the authors want to assess biodiversity loss from a land use perspective in a single-indicator method. GLAM as a multi-indicator method takes various aspects into account to assess biodiversity loss. GLAM uses data from GLOBIO4, the latest update of GLOBIO. Both methods use data from PREDICTS database and others, which are in common with former methods. Additionally, the JRC has identified BioMaps as a good basis for biodiversity assessment to be incorporated into the EF method. This is an advantage for this method. Therefore, for high level risk biodiversity screening, e.g. for companies, the authors of this study recommend using the UNEP-GLAM method and BioMAPS within the EF methodology (once available), along with the use of a broader methodological toolkit (like certification schemes and field measurements) to assess biodiversity impacts to provide a more robust answer to the specific research question.

Overall, significant progress has been made in biodiversity assessment within LCA in the last decade, but challenges remain related to data gaps, uncertainty, impact pathway modelling, methodological choices, and interpretation. Given the rate at which the development takes place, it is recommended to regularly check for updates in LCIA methods, models and data, to be aware of the latest developments. Furthermore, during the use of LCA to assess impacts on biodiversity, it is recommended to acknowledge the uncertainty in the current models and methods. Additionally, the approach to assess biodiversity impacts depends on the goal, scope and research question of the assessment.

Similar to other choices in LCA, the choice of method directly influences the hotspot identification and therefore strategy and resource allocation. To avoid biased choices, sensitivity analysis by using different methods and adding other biodiversity evaluations are recommended. Current methods can be applied to generate an understanding of biodiversity impacts of product value chains, but should be confirmed with additional assessments. It is not recommended to inform consumers using LCA approaches, due to a multitude of challenges based on the current state of biodiversity assessments in LCA. For the development of mitigation strategies, it is recommended to use scientifically proven measures stimulating biodiversity on site or throughout the value chain. A broader application of biodiversity assessment methods in LCA, through for example case studies, improves the understanding of the methods and allows refinement of the methods as well as validation of the LCA methodologies with other biodiversity assessment approaches and methods.

2 Introduction

The chemical and materials industry is at a pivotal moment, driven by environmental concerns, regulatory requirements, feedstock availability and the urgent need for long-term sustainability and resilience. Reducing dependency on fossil-based feedstocks is a top priority regarding i) the reduction of greenhouse gases, and ii) the strategic autonomy of Europe from third countries. Besides recycling and the capture and use of carbon dioxide (CO_2), biomass presents a compelling alternative feedstock, offering a renewable carbon source for chemical and materials production. Actually, a share of about 20% global biomass is estimated for a net-zero bioeconomy by 2050 (Harrandt, Carus et al. 2024) – a goal which can be realistically achieved in a sustainable manner with a moderate high-tech agriculture according to a recent joint scientific background report by the Biobased Industry Consortium (BIC) and the Renewable Carbon Initiative (Carus, Porc et al. 2025). Nevertheless, biomass use for the defossilisation of the chemical and materials industry requires careful management to avoid (further) negative impacts on biodiversity and ecosystems. How can sufficient biomass production be guaranteed alongside biodiversity protection? Although today only a very small proportion of the total global biomass is used for the chemical and materials industry (11%; in relation to 15% food, 56% feed and 16% bioenergy) (Skoczinski, Carus et al. 2025), the bio-economy could become a forerunner for biodiversity protection, as it has both the responsibility to act sustainably and use the tools to protect both, biodiversity and climate.

The following report is the second of three interconnected parts. Part one summarises current knowledge of causes and consequences of biodiversity decline, global and European policies in support of bioeconomy and/or biodiversity, and the trade-off between biomass production and biodiversity conservation. Part two has the goal to transparently show the efforts with regards to biodiversity assessment for a terrestrial environment in Life Cycle Assessment (LCA), and subsequently discuss applicability as well as open research questions. Part three lists agricultural and forestry-related measures that individually or in combination can protect, or even increase biodiversity without compromising the biomass production, and discusses best-practises on the basis of global case studies.

Biodiversity is “the variability among living organisms including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part” (Brondizio, Diaz et al. 2019). This variability includes different aspects of biological and ecosystem diversity (WWF 2024):

- Diversity of species, i.e. the number, abundance and combination of species in a specific area.
- Diversity within species and populations of the same species regarding genetic composition, physiological traits, behaviour, ecological roles and functions (e.g. occupation of an ecological niche, or position within the food web).
- The diversity and functionality of ecosystems within an area, including different types of terrestrial, marine and freshwater ecosystems.

Local and global biodiversity are threatened by five main drivers, identified by the intergovernmental science-policy platform on biodiversity and ecosystem services (IPBES): Those drivers are

- changes in land and sea use,
- climate change,
- direct exploitation of organisms,

- invasion of alien species and
- pollution.

These drivers are influenced by a multitude of different pressures, like water use, land use, carbon dioxide emissions, use of fertilizers and many others. Some of the aforementioned drivers are (currently) quantifiable through LCA impact categories like climate change or land use. However, there is no (scientific) consensus on the biodiversity metric and methodology yet which make it difficult to quantify biodiversity impacts and therefore consider the impact in business decisions.

Many attempts have been made, and are ongoing, to include biodiversity into the Impact Assessment of LCAs. They all have different strengths and weaknesses and have in common that they have not become widely accepted. As defined in the offer to the RCI, the goal of task 2 is to transparently show the efforts with regards to biodiversity assessment in LCA for a terrestrial environment. Following methods from the last ten years are included:

- ReCiPe2016 (Huijbregts et al., 2017),
- IMPACT World+ (Bulle et al., 2019),
- LC-IMPACT (Verones et al., 2020),
- Product Biodiversity Footprint (Asselin et al., 2019)
- Biodiversity Impact Assessment+ (Winter et al., 2018)
- BioMAPS (Maier, 2023) & possible Biodiversity Loss Potential within the LANCA method & relation to PEF
- Global Extiction Potential (Verones et al., 2022)
- UNEP-GLAM (2025)
- Biodiversity Value Increment (Lindner et al., 2019)

According to the offer, a literature review is done on the aforementioned methods.
The methods are evaluated with regard to

- Overall integration of biodiversity levels and drivers
- Data analysis
- Exemplary regionalisation analysis
- Overall applicability & usage – e.g., usage in software tools like Simapro / sphere & list of reference, where the method already has been applied.
- General aspects

The above mentioned methods are described briefly in chapter 4. The development of LCA specific characterization factors are exemplarily explained with a focus on land use, as the indicator land use is described in each investigated method and this can be used to compare the different methods. For interested readers, who want to understand fully the formulas, we recommend to read the papers in which the methods are described. Depending on the method, other impacts might be included in the land use indicator. Biodiversity impacts via other indicators are not explicitly described in the method description chapter, but are mentioned in the comparison chapter / annex. A comparison of the methods is reported in chapter 5. The comparison chapter contains the impact categories: land use, water use, GHG emissions, toxic emissions, nutrient emissions and other air emissions. Chapter 6 contains the discussion section. Finally, the report is summarized, concluded and recommendations are stated in chapter 7.

3 Short introduction to biodiversity in LCA

Life Cycle Assessment (LCA) is a method to quantitatively assess (based on physical metrics) the potential environmental impact of a product or service throughout its entire life cycle by quantifying all inputs and outputs of material and energy flows and assessing how these flows affect the environment (Figure 1). It assesses environmental impacts such as climate change or eutrophication as well as the impacts on natural resources and/or human health.

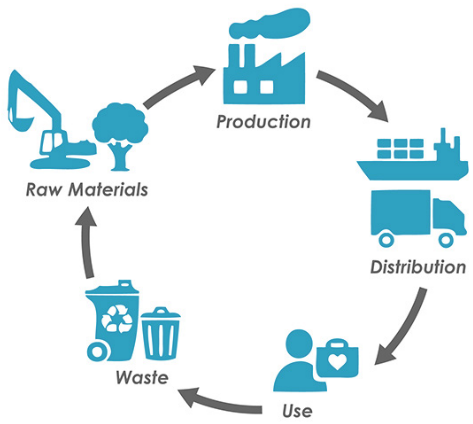

Figure 1: The life cycle model

LCA is an internationally standardized method laid out in ISO 14040:2006 and ISO 14044:2006. The strength of LCA is that it studies a whole product system. This avoids suboptimization that may be the result if only a few processes are focused on.

An LCA study consists of four different phases:

1. Goal and scope definition
2. Life Cycle Inventory analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation of the results

In the goal and scope definition phase, the product to be studied and the purpose of the study are decided on. The functional unit for which the study refers is also defined. Many other choices related to the modelling are made during the goal and scope definition. In the life cycle inventory analysis (LCI) phase, the system model is built according to the requirements of the goal and scope definition. The system model is a flow model of the system with certain types of system boundaries. The result is a mass and energy balance for the system. The Life Cycle Impact Assessment (LCIA) aims to indicate the impacts of the environmental loads quantified in the inventory analysis by classifying the inventory parameters to the type of environmental impact that they contribute to and finally by calculating the relative contribution of the emissions and resources consumption to each type of environmental impact (characterization). Such calculations are based on scientific models of cause-effect chains in the natural system. Sometimes these results need to be interpreted and aggregated even further. This can be done in different ways, for instance with formalized and quantitative weighting procedures. The last phase is the interpretation in which the findings of both, the inventory analysis and the impact assessment are evaluated, in relation to the defined goal and scope, in order to reach conclusions and recommendations. The relationships between these phases have been illustrated in Figure 2 which shows that an LCA study is a highly iterative process among the different phases.

The results of an LCA can be used for revealing hotspots which can lead to identification of approaches to mitigate the impacts for the development of less harmful processes and products (product and process design and decision making). The LCA may also enable the comparison of different products (benchmarking) and can support marketing and public policies, for instance, to support LCA-based eco-labelling. Another important application of LCA is that of learning, e.g. exploring the environmental properties of the product system studied and learning about relationships of the production system. It must be noted that "positive" LCA results do not necessarily mean a process is sustainable. One limitation of the LCA is that the method is restricted to quantify only the ecological aspect of sustainability, thus, excluding from the assessment economic and social factors other than that used as basis for weighting environmental impact categories.

For the evaluation of the environmental performance via LCA, a long list of so called elementary flows is modelled that enter the product system in scope coming from the ecosphere or leave it from the product system in scope to the ecosphere. In the LCIA stage, these flows are categorized to different impacts, if there are any. Within a LCIA method, a set of impact categories and the contribution of elementary flows to these impact categories is defined. The height of contribution of each elementary flow is calculated through defined characterisation factors (CF). The characterisation factors are gathered and developed by different scientists and when applied, convert the elementary flow to the common unit of the impact category indicator. Depending on the selected LCIA method, different impact categories are available and also the CFs might differ within each impact category from LCIA method to LCIA method. The environmental performance can be analysed at a so called midpoint or endpoint level and for each level, different characterization factors exist. Midpoint level characterisation factors are located along the impact pathway. According to Goedkoop et al. 2009, this is usually "at the point after which the environmental mechanism is identical for all environmental flows assigned to that impact category" (Goedkoop et al. 2009). Characterisation factors for endpoint level are located further along the impact pathway, thus requiring additional modelling, thereby increasing the uncertainty.

This logic is exemplarily shown in Figure 2. Elementary flows are entering and leaving the system boundary of the life cycle of interest. The elementary flows are classified to their contribution and then multiplied with a specific CF to receive results for the midpoint impact categories, which they contribute to. Some LCIAs have endpoint categories, which are located further at the cause-effect chain. They either are derived with specific CFs directly from elementary flows (LC-IMPACT model) or from multiplying defined factors with the midpoint CF (ReCiPe2016 model) which is basically another characterization step. The uncertainty increases with the length of the modelled impact pathway. In general, the characterization factors express the relative difference from the amount entering or leaving the system boundary to a reference. The reference unit is defined in the LCIA method. For global warming it is usually kg CO_2 eq..

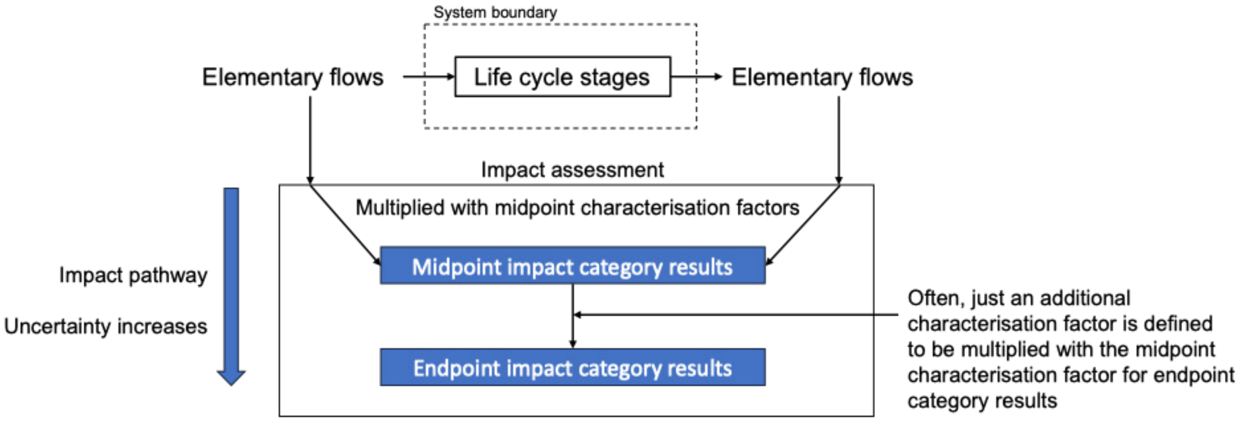

Figure 2: Connection between elementary flows of a product system, midpoint and endpoint impact category results

With regards to biodiversity assessment in LCA, midpoint and endpoint characterization factors play a role. In specific LCIA methods like ReCiPe, the endpoint impact category "ecosystem quality" is defined, which partly covers biodiversity aspects.

A lot of LCIA methods address impact categories like climate change, land use, water use, eutrophication and ecotoxicity to name a few, which have an effect on biodiversity loss. However, not all of the existing LCIA methods come to the conclusion that biodiversity can be assessed with their impact categories, as they cover only parts of the biodiversity drivers and some impact pathways leading to biodiversity loss are not fully understood, yet. Only very limited LCIA methods are dedicated to biodiversity impacts. Pressures on biodiversity, that are already implemented in LCA through some impact categories, are visible in Figure 2 from Winter et al., 2019. The white and light grey squares show pressures / drivers like land transformation, fresh water use, acidification, water use, land use, carbon dioxide emissions, eutrophication, photochemical ozone formation, that are already implemented in LCA as impact category through specific LCIA methods. Dark grey squares indicate pressures that are investigated to be included as impact categories in LCIA methods, but the impact pathways are not yet fully understood or data is not yet fully available.

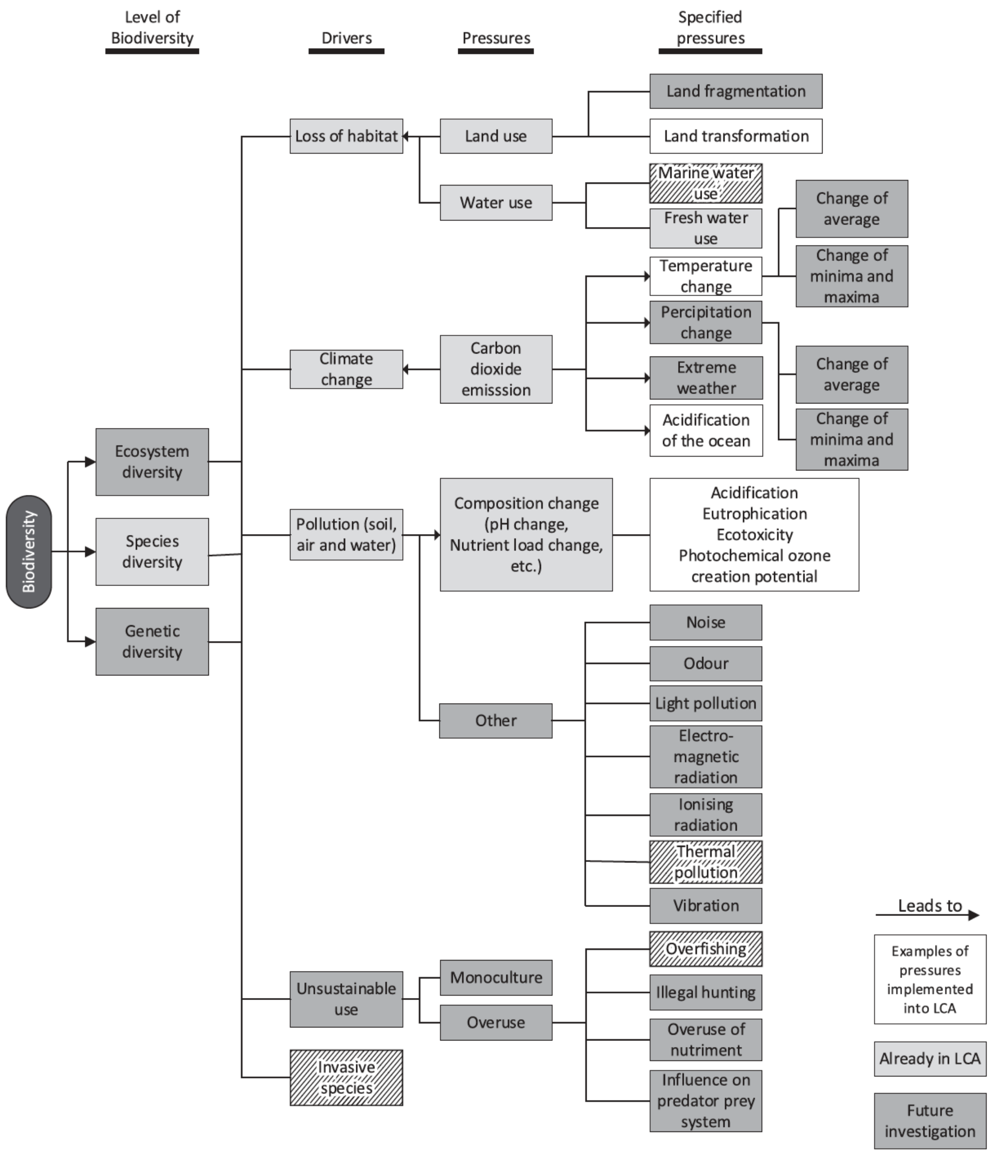

Figure 3: Biodiversity complexity broken down into several drivers and pressures on biodiversity and the status of their implementation into LCA (Winter et al.2019)

According to IPBES, land use and land use change has had the largest relative negative impact on nature and hence is the biggest driver of biodiversity loss (IPBES 2019). To focus the scope, this report focusses on terrestrial biodiversity loss. Freshwater or marine biodiversity loss are out of scope of this document.

As exemplary impact category for terrestrial biodiversity loss, land use is selected. This comparing the different LCIA methods, as land use related biodiversity loss is covered by all evaluated methodologies. The impact pathway for land use is defined through the UN Environmental Life Cycle Initiative (former UNEP-SETAC Life Cycle Initiative). It defined land use impacts as a function of quality (Q), area (A) and time (t). Quality can represent for example soil quality, water storage capacity or biodiversity. Two types of land use are differentiated: Land transformation and land occupation. Whereof land transformation is the change from a reference situation to the new state over a specific time. Occupation includes the time frame in which it is used differently than before.

4 Methods description

The aforementioned methods are described briefly in the following chapters. The investigated methods can be categorized into multi-indicator methods and single-indicator methods. Multi-indicator methods are those methods that include various indicators like climate change, water use, land use and others, such as ReCiPe, LC Impact, Impact World+ and GLAM. Some of their included indicators are biodiversity related, but not all of them. The here investigated single-indicator methods are methods, that focus on modelling specifically biodiversity and they attempt to fill an accuracy gap. They can be either integrated into a multi-indicator method, like BioMAPS (3.6) which is planned to be integrated into PEF or GEP, which is an additional endpoint measure that can be incorporated into many multi-indicator methods, or they are left as stand-alone for the user to decide where and if they want to plug them in (e.g. into the PBF (3.4)). The PBF is a multi-indicator method, using an existing LCIA method of choice to quantify three of the five main biodiversity drivers and additionally includes qualitative aspects for the remaining two biodiversity drivers.

The development of LCA specific characterization factors are exemplarily explained with a focus on land use, as the indicator land use is described in each investigated method and this can be used to compare the different methods. For interested readers, who want to understand fully the formulas, we recommend to read the papers in which the methods are described. Depending on the method, other impacts might be included in the land use indicator. Biodiversity impacts via other indicators are not explicitly described in the method description chapter, but are mentioned in the comparison chapter / annex.

4.1 ReCiPe 2016

The ReCiPe method is one of the reknown LCA impact assessment methods, which provides harmonized midpoint and endpoint CFs for 18 midpoint and three endpoint categories and is therefore a multi-indicator method. ReCiPe was first developed in 2008 by Rijksinstituut voor Volksgezondheid en Milieu, Radboud University Nijmegen, Leiden University and Pré Consultants. An update of that method was done in 2016, in which the data and scientific models were updated. ReCiPe defines three types of cultural perspective (individualist, hierarchist and egalitarian). For this study, the hierarchist perspective is taken into consideration, as it is based on scientific consensus with regard to the time frame (100 years) and plausibility of impact mechanisms. (Huijbregts et al. 2017, Huijbregts et al. 2017a)

The 18 ReCiPe2016 midpoint categories, their contribution to specific damage pathways and the final endpoints are visualized in Figure 2. The midpoint categories are particulate matter, tropospheric ozone formation, ionising radiation, stratospheric ozone depletion, human toxicity (cancer and non-cancer), global warming, water use, freshwater ecotoxicity and eutrophication, tropospheric ozone, terrestrial ecotoxicity and acidification, land use / transformation, marine ecotoxicity, mineral resources and fossil resources. At endpoint level, there are three areas of protection defined: human health, ecosystem quality and resource scarcity. Whereas ecosystem quality covers some biodiversity aspects and is of interest within this study. ReCiPe provides CFs that are representative for the global scale and CFs that are representative at a country and continental scale.

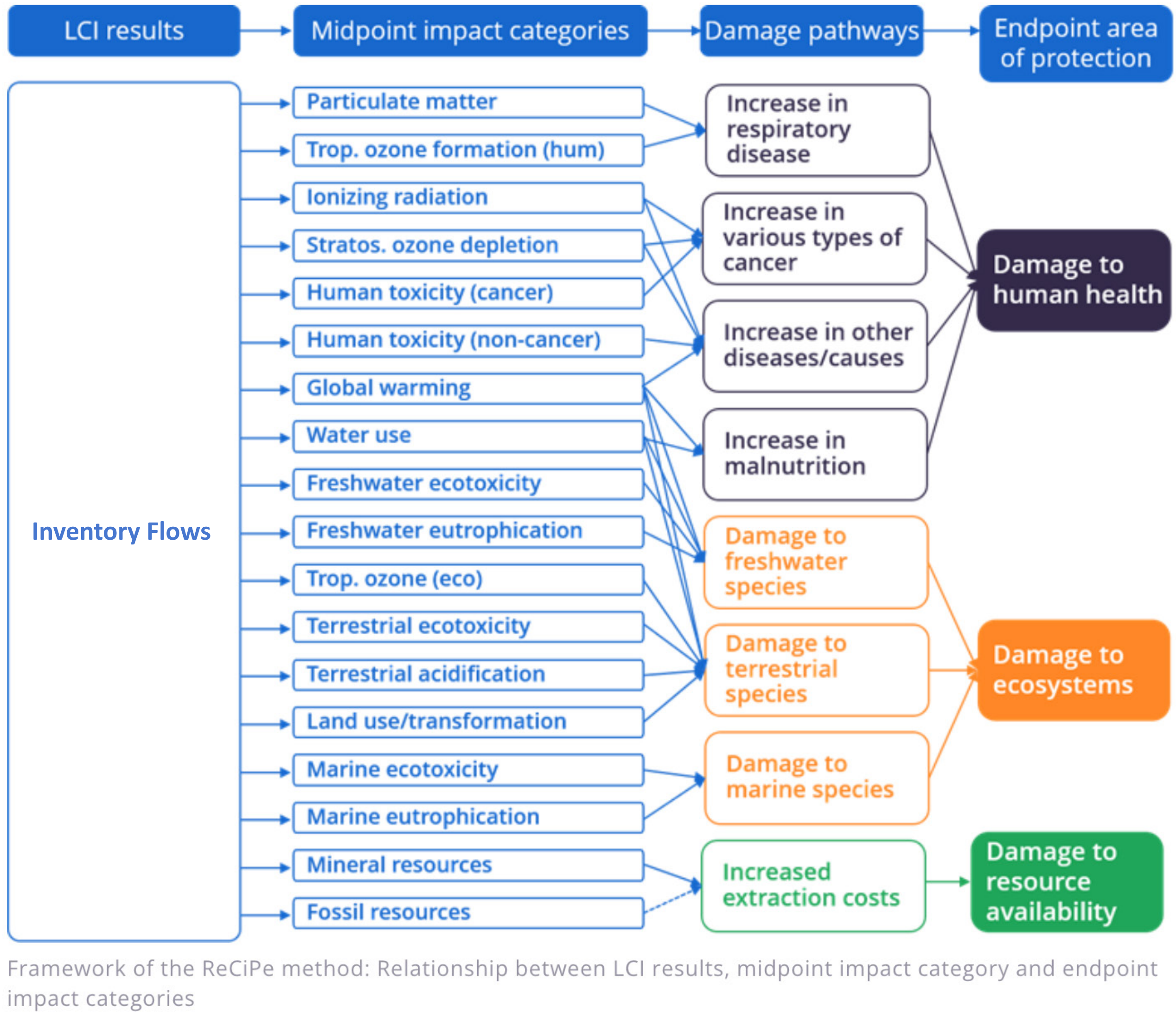

Figure 4: Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection (Huijbregts et al. 2017a). Whereas damage to ecosystem is closest to biodiversity loss with the damage pathways damage to freshwater, terrestrial and marine species. Those are influenced by the midpoint impact categories global warming, water use, freshwater ecotoxicity and eutrophication, tropospheric ozone, terrestrial ecotoxicity and acidification land use / transformation and marine ecotoxicity and eutrophication.

To calculate ecosystem quality, damage pathways need to be established. Within ReCiPe2016, the endpoint "Damage to ecosystems", in orange, belonging to the area of protection of ecosystem quality, is influenced by the damage pathways "damage to freshwater species", "damage to terrestrial species" and "damage to marine species". Those three damage pathways are influenced by the midpoint impact categories global warming, water use, freshwater, terrestrial and marine ecotoxicity, freshwater and marine eutrophication, tropospheric ozone, terrestrial acidification and land use / transformation, which cover biodiversity pressures (Huijbregts et al. 2017).

For the calculation, the environmental mechanism from midpoint (i.e. land use) to endpoint (i.e. ecosystem quality) at the cause-effect pathway are considered to be identical for all stressors per impact category, which is expressed mathematically through a factor. Therefore, the endpoint characterisation factors (CFe) are derived from midpoint characterisation factors (CFm) multiplied with a factor per impact category (F).

Consequently, endpoint results have a higher uncertainty than midpoint results. In ReCiPe the modelling of the environmental fate of emitted substances is included in the calculation of the mid-point characterization factor, when applicable (i.e. for eutrophication and acidification indicators).

$$CFe=CFm * F$$

The authors of the ReCiPe method were able to define midpoint to endpoint factors for all impact categories for the endpoint ecosystem quality, see Table 1. The unit for ecosystem quality is the local species loss integrated over time (species * year). Exemplarily, the land use CF calculation for ecosystem quality is explained in Annex 7.1 (Huijbregts et al. 2017)

Table 1: ReCiPe 2016 constants for midpoint to endpoint characterisation factors of the standard (hierarchist) characterisation factors. (Huijbregts et al. 2017)

	Unit[1,2]	
Ecosystem quality: terrestrial		
climate change	species.yr/kg CO_2 to air	2.8E-09
photochemical ozone formation	species.yr/kg NO_x to air	1.3E-07
acidification	species.yr/kg SO_2 to air	2.1E-07
toxicity	species.yr/kg 1,4-DCB to industrial soil	5.4E-08
water use	species.yr/m^3 water consumed	1.4E-08
land use	species/m^2 annual crop land	8.9E-09
Ecosystem quality: fresh water		
climate change	species.yr/kg CO_2	7.7E-14
eutrophication	species.yr/kg P to fresh water	6.1E-07
toxicity	species.yr/kg 1,4-DCB to fresh water	7.0E-10
water use	species.yr/m^3 water consumed	6.0E-13
Ecosystem quality: marine		
toxicity	species.yr/kg 1,4-DCB	1.1E-10

Overall integration of biodiversity levels and drivers

Of the three levels of biodiversity, only species diversity is addressed. It is a multi-indicator method and of the five main drivers of biodiversity, three are (partly) assessed: global warming (climate change), land use / transformation and pollution through ecotoxicity, eutrophication, acidification and other pollution. The drivers invasive alien species and direct exploitation of organisms are not addressed with this impact assessment method. No additional pressures for biodiversity are addressed.

Exemplary data analysis with regard to land use indicator

In ReCiPe2016, the midpoint CFs for land use are derived from species richness data from well-studied species like plants, vertebrates (mammals and birds) and invertebrates (mainly arthopods) (de Baan et al. 2013, Elshout et al. 2014), resulting in overrepresentativeness of these groups. Other groups like reptiles and amphibians are not included at all. The generated CFs are approximated for the impact of land use on total species richness, as the taxonomic groups react differently to land use and land use change depending on their size and conditions. CFs are provided for several land use types like used forest, pasture and meadow, annual crops, permanent crops, mosaic agriculture and artificial areas. If, due to a lack of information, it is not possible to distinguish between reference vegetation types during an assessment, global average CF values are recommended to use while modelling the LCA. For more information, please see ReCiPe2016 method. (Huijbregts et al. 2017)

The local land use covers land transformation, occupation and relaxation, for which CFs are provided within ReCiPe and based on models from several scientists: de Baan et al. (2013), Elshout et al. (2014), Köllner et al. (2007) and Curran et al. (2014). Exemplarily, the study from De Baan et al.(2013) is investigated.

The study from de Baan et al. (2013) is based on the framework of LCIA of land use, developed by the United Nations Environment Programme (UNEP) / Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative working group. They describe an approach to quantify biodiversity impacts based on different species in LCIA in different regions. In their study, two data sources were combined: GLOBIO3 biodiversity database based on a quantitative review of literature (Alkemade et al. 2009) and national biodiversity monitoring data of Switzerland. For the GLOBIO3 database, data from peer-reviewed empirical studies are used which compare the biodiversity of different land use types with a (mostly) "undistorted" reference situation within the same study site. The impact of land use is expressed as the relative change in species richness or abundance of a range of different taxonomic groups. De Baan et al. (2013) localized the studies and assigned the corresponding WWF biome and ecoregion with that data. Even though nine of 14 biomes with 644 data points on different land use types and 254 data points on reference situations from 195 publications were assessed, the authors of de Baan et al. (2013) found that the data was not evenly distributed (a lot of data was available for the tropics, less data available for the boreal zones) and completed the analysis with an indicator from the National Biodiversity Monitoring Data of Switzerland to assess the species diversity in Switzerland. The BDM indicator covers two biomes (temperate broadleaf and mixed forests and temperate coniferous forests). It is based on a grid of 1600 evenly distributed sampling points over Switzerland which results in a size of 10 m² for each sampling point. For each of this point, species richness, vascular plants, moss, mollusks and the land use type were recorded. In de Baan et al. (2013) the authors made this data comparable to the GLOBIO3 data, by reclassifying and restructuring it. For more information, see de Baan et al. (2013).

Exemplary regionalisation analysis with regard to land use indicator

According to ReCiPe2016, the CFs are based on global scale data and for some impact categories on continent or country scala. For example, climate change has a global impact and is modelled as a globally homogeneous stressor. A global factor implies the same impact of a pressure regardless where it takes place on earth. At the local level, land use change, habitat quality and species diversity are modelled. For land use, species group or land use type specific CFs are available see Annex 7.1. Regionalised factors lead to more accuracy in the results, as not all impact categories affect the same impact of pressure in different localities.

Overall applicability & usage

ReCiPe2016 can be used in LCA software tools like Simapro, openLCA or sphera and is therefore easily accessible for LCA practicioners. It is used in several studies like:

- Obaid et al. 2025
- Vinci et al. 2024
- Bałdowska-Witos et al. 2023
- Bałdowska-Witos et al. 2020

Generally, ReCiPe2016 provides

- Widely accepted multi-indicator LCIA method with 17 midpoint and 3 endpoint indicators
- ecosystem quality as endpoint indicator, which partly covers biodiversity loss in species * year, derived from nine midpoint indicators
- three of the five drivers that are indirectly addressed via impact categories, but not comprehensively
- global generic CFs for most of impact categories, country specific CFs for some impact categories, local / land type specific CFs for land use
- widely usage in LCA software, as it is integrated in tools like SimaPro, OpenLCA and sphera
- data gaps: focuses on species level, lacks ecosystem and genetic diversity

4.2 IMPACT World+

IMPACT World+ is a regionalised impact assessment model for both midpoints and damage levels and therefore is a multi-indicator method. The LCIA method has several goals, which include providing a uniform modelling structure including fate, exposure, exposure response and severity across ecosystem quality related impact categories as well as the adaptation of functionality based assessment (consumption/competition/adaptation) for impacts generated from the loss of an ecosystem service.

In Figure 4, it can be seen that the LCIA method defines three areas of protection (Human Health, Ecosystem Quality and Resources & Ecosystem Services). As such, biodiversity is not specifically defined as an area of protection, however ecosystem quality is used as an endpoint indicator. Biodiversity is explicitly mentioned in the land occupation and transformation indicators for both midpoint- and damage level indicators. In the methodological description, the authors explicitly state the following "Land occupation and land transformation impacts on terrestrial biodiversity are considered as an acceptable proxy for all the land use impacts on ecosystem services" (Bulle et al. 2019). These indicators contribute to damages on ecosystems quality, along with other indicators such as climate change, eutrophication, acidification and water availability. The damage level indicators include impact pathway modelling to a damage level and thus have different units, for example Disability-Adjusted Life Year (DALY) and Potentially Disappeared Fraction of species (PDF). It must be noted that the figure below does not show any arrows linking damage level indicators to the resource and ecosystem services area of protection.

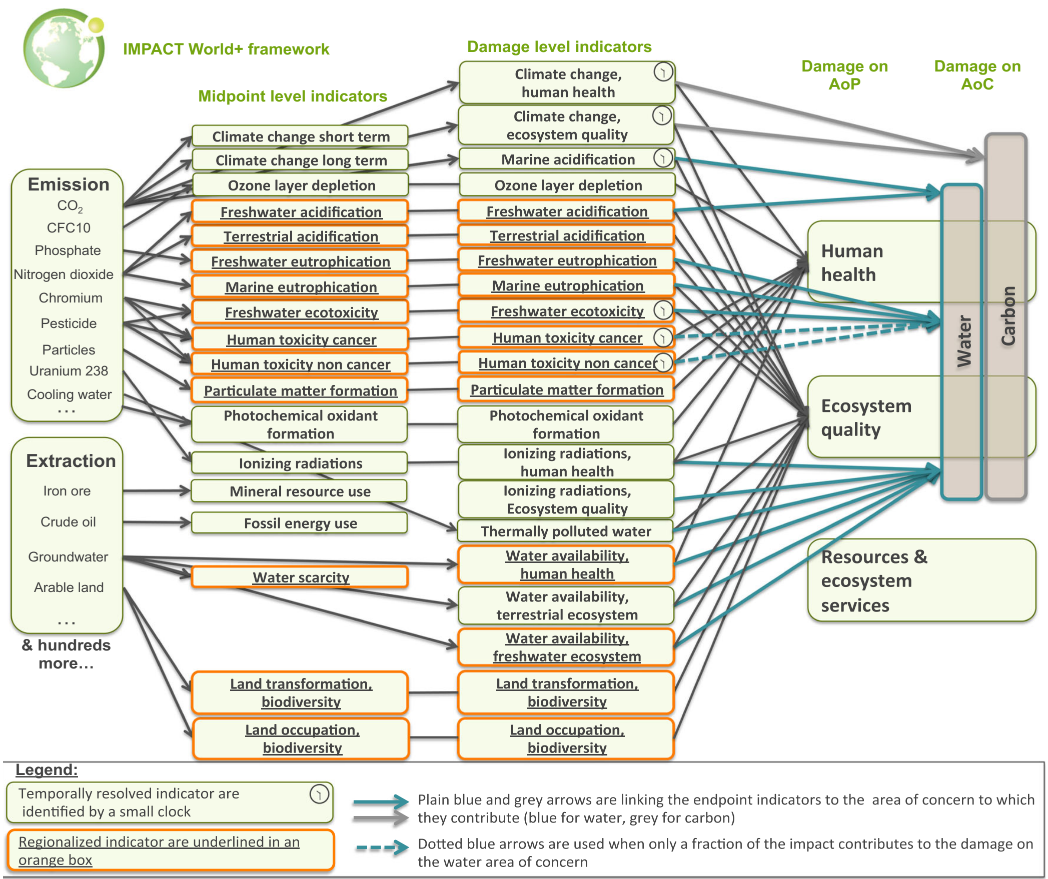

Figure 5: Schematic overview of the IMPACT World+ framework (Bulle et al., 2019)

The authors have derived regionalised characterisation factors (boxes shown in orange in the figure above) for all damage level indicators linked to ecosystem quality except for climate change, marine acidification and terrestrial water availability. The formula to quantify the CFs for the damage level includes a Severity Factor (SF), Exposure Response Factor (XRF), Exposure Factor (XF) and a Fate Factor (FF):

$$CF_{sk} = 1 * SF_{sk} * ERF_{sk} * XF_{sk} * FF_{sk}$$

In the formula above, s represents elementary flows whereas k represents impact categories. Simplified, the Fate Factor matrix models where elementary flows end in the environment and how it changes over time. The exposure factor considers how much of a substance becomes available to be absorbed by organisms. The exposure response matrix quantifies the potential of the organism or ecosystem to be affected by the exposure and the severity factor aggregates the responses into damage level units. The characterisations factors are regionalized both at midpoint and at damage level, as far as possible.

For land use, two midpoint level impact categories are considered; occupation and transformation (excluding damage level impact categories which are considered interim by the authors). For land occupation, 6 different land use flows are considered (reference is de Baan et al. (2013)) with Olsen biomes as native resolution. The aggregation is performed by assessing the surface areas of the different Olsen biomes covered in the country/continent/globe. For land use transformation, 12 elementary flows are covered. The rest is the same as the land occupation indicator, for more details see Annex 7.2.

In table two of the publication, also included in Annex 7.2, the authors describe the linking of the midpoint, to damage level indicators as well as their respective units and the fate factor, exposure factor, exposure response and severity factor. For land use, the midpoint level characterisation factor unit is m² arable land*year/(m2occupied*year), whereas the damage level characterisation unit is PDF*m²*yr/(m2occ*yr). The fate factor, exposure factor, exposure response and severity factor are calculated with a single formula. It is calculated by dividing the damage equivalents by the area occupied multiplied with the time. For land use transformation, all units which consider occupied land are replaced with areas which are transformed. Furthermore, the fate factor is calculated by multiplying the area occupied with the time and divided the area transformed. For the exposure-, exposure response-, and severity factor the same formula is used, which is calculated similarly to the formula used for land use occupation.

In the results, the authors provide an overview the spatial variability of the impact characterisation factors for freshwater acidification, terrestrial acidification, marine eutrophication, freshwater eutrophication and land occupation on the ecosystem quality. The results are shown in Annex 7.2 and indicate that the spatial variability is larger than the variability among the elementary flows, leading the authors to conclude that the place where impacts occur may be more relevant than the type of impact occurring.

Since the first publication in 2019, the method has been updated several times, releasing a version 2.0 as well as a more recent release of version 2.1 (IMPACT World+ 2025). Most of the updates are related to the updating of the CFs based on the latest available information, such as the implementation of the latest IPCC CFs for climate change. Land occupation and transformation CFs have also been updated several times. With the release of version 2.1, various new indicators are included in the method, including the physical effect of plastics on biota based on the MarILCA working group results and the impact of fisheries activities on biodiversity. Since this report focusses on terrestrial biodiversity, and the MarILCA and the impact of fisheries both primarily concern marine biodiversity, the details are not discussed here. For more information, see MarILCA (2025) and Standford-Clark et al. (2024).

Overall integration of biodiversity levels and drivers

In terms of the three levels of biodiversity, the IMPACT World+ method only considers the species level. It is a multi-indicator method and the included drivers of biodiversity loss are climate change, habitat change (through land occupation and transformation), and pollution. Pollution is covered through the inclusion of acidification (marine, freshwater and terrestrial), eutrophication (marine and freshwater), ecotoxicity and microplastic in aquatic environments. Damages on ecosystem quality through water availability impacts are assessed through the combination of several methods; for the impacts of freshwater consumption on freshwater ecosystems through the use of the work of Hanafiah et al. (2011), groundwater through the model of van Zelm et al. (2011) to assess the water scarcity impacts on on terrestrial ecosystems and the model of Verones et al. (2010) to assess the impact of thermally polluted water. With the update of the method, the impact of fisheries on biodiversity were included, thus covering one aspect of overexploitation as well.

Exemplary data analysis with regard to land use indicator

Since many damage indicators are combined in the IMPACT World+ method, this section provides a brief overview of the studies used in the methodology, focusing on land use. Other aspects included in the ecosystems quality area of protection are detailed in Annex 7.2

The climate change damages on ecosystems quality are based on regional studies aiming to predict the exitiction of species due to increases in temperature (Thomas et al. 2004), who compile reagional studies predicting the extinction of species related to increases in temperature. The native resolution is global and 212 elementary flows are included.

The CFs for land use are based on de Baan et al. (2013), similar as the ReCiPe methodology described above. The authors argue that those are preferred over the regional and global CFs from Chaudhary et al. (2015), to ensure “coherence with the other impact categories on the physical meaning of impact scores at the damage level.” The difference between the CFs reported by de Baan et al. (2012) and Chaudhary et al (2015) are that Chaudhary base the factors on (semi-) irreversible disappearance of species at regional or global scale, expressing the regional PDF indicator as fraction of species disappeared forever from a region.

In contrast, the IMPACT World+ framework quantifies the temporarily disappearance of species over a given surface and time. The authors argue that the approach of Chaudhary would result in an infite impact, as the disappearance is permanent. The authors argue against applying regeneration times to overcome this issue, by stating that the regeneration time supposedly applies to ecosystems rather than irreversibly disappeared species. They further note that applying the regeneration times would lead to much lower impacts as only a small fraction of species affected by land occupation or transformation will permanenty disappear from the affected region. In the land use impacts, there is no need to consider fate and exposure, as effects occur directly in the environmental compartment where they are reported. The biodiversity loss is therefore directly related to the land occupation. Midpoint indicators can be obtained by dividing damage values by the global average CF for arable land, thereby normalizing damage values with a reference towards arable land. Land transformation impacts are based on Curran (2010) as these impacts are considered longterm impacts and ecosystem recovery after occupation likely occurs in the far future.

Exemplary regionalisation analysis with regard to land use indicator

Global, continental, country and native resolutions are available for all regional impact indicators with the associated uncertainty due to spatial variability. The characterisations also show that the place where an emission occurs may be more relevant than the emission that occurs, which could provide valuable insights and guidance for more specific regionalization of elementary flows in the modelling of an LCA to reduce uncertainty.

Overall applicability & usage

The IMPACT World+ method is available online and implemented in some LCA software (openLCA, SimaPro, Brightway2, ExioBase and ecoinvent). Furthermore, the method is regularly updated to keep CFs up to date and the method has been extended recently to cover impacts of fisheries as well as marine plastic littering. It is used in studies like:

- Mason et al. 2024
- Silva, D., & Patouillard, L., (2017)

Generally, IMPACT World+ provides

- Multi-indicator method: LCIA method with 18 midpoint and 21 damage level indicators, related to damages on three areas of protection and 2 areas of concern
- Ecosystems quality as defined as area of concern, expressed as PDF*m²*yr, covering some biodiversity aspects
- Regionilisation of the characterization factors through the use of SF, EF, EXF and FF matrices, enabling application at various spatial scales: global, country, regional and native resolutions.
- Coverage of land use and climate change drivers, partial inclusion of pollution drivers. Some inclusion of overexploitation drivers, no inclusion of alien species.
- Widely available in LCA software as the LCIA method is integrated in tools like SimaPro and Open LCA
- data gaps: focuses on species level, lacks ecosystem and genetic diversity

4.3 LC-IMPACT

The LC-IMPACT method is the result from the EU-FP7 funded project "Development and application of environmental LifeCycle Impact assessment Methods for imProved sustAinability Characterisation of Technologies (LC-IMPACT)". Similar to ReCiPe2016, it shall "provide a global life cycle impact assessment methodology for the three main areas of protection (human health, ecosystem quality, resources), including spatially differentiated information wherever necessary and feasible" (https://www.lc-impact.eu/index.html). It is a damage-oriented method, multi-indicator method, focusing on endpoints and areas of protection as pathways. The involved scientists – a working group of Francesca Verones – aimed at creating a consistent and transparently documented LCIA method. They collected characterization models for all available impact pathways. To gain a complete method, they added characterization models for categories which were not covered from the project. With regard to other LCIA methods, this method contains different models for impact pathways with greater regionalization for example for land use. All their data and documents are available at Zenodo and the framework can be downloaded for free. (Verones et al. 2020a)

The 11 LC-IMPACT impact categories and their contribution to the areas of protection are visualized in Figure 5. Seven impact categories include spatial differentiation at various levels of spatial scale. All impacts are quantified at a damage level. The impact categories are climate change, ozone depletion, ionizing radiation, photochemical ozone formation, particulate matter formation, acidification, land stress, toxicity, eutrophication, water stress and mineral resource scarcity. Eutrophication includes freshwater and marine eutrophication. Ecotoxicity includes impacts on freshwater, terrestrial and marine ecosystems. At endpoint level, there are three areas of protection defined: human health, (terrestrial, freshwater, marine) ecosystem quality and natural resources. According to LC-IMPACT, terrestrial ecosystem quality is influenced by climate change, photochemical ozone formation, acidification, land stress and toxicity. Damage to ecosystem quality is expressed as global species extinction equivalents (based on potentially disappeared fraction of species). Ecosystem quality covers aspects from biodiversity loss. (Verones et al. 2020a)

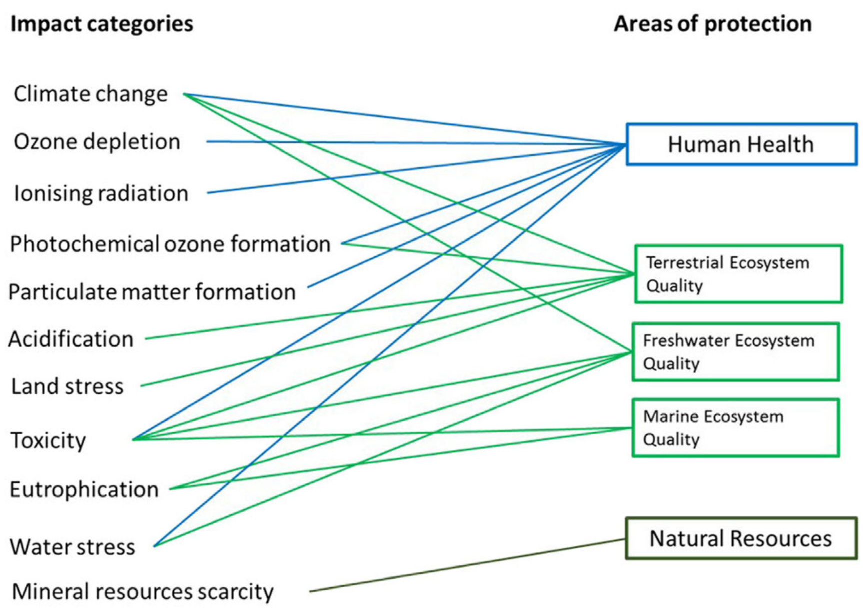

Figure 6: Overview of the impact categories and areas of protection covered in LC-IMPACT. For ecosystem quality, three types are defined: terrestrial, freshwater and marine. (Verones et al. 2020a)

Damage to ecosystem quality is calculated with a specific CF for each impact category. The equation to calculate a CF for ecosystem quality according to LC-IMPACT is as follows:

$$CF_{ecosystem\ quality} = VS * EF * XF * FF$$

Whereas

- VS stands for a vulnerability factor and represents the species loss from global level, per species. It is calculated from species richness and vulnerability score of that taxonomic group per ecoregion and divided by their global species richness.
- EF is an effect factor per species
- XF is an exposure factor (=1 for some impact categories like land stress, as they don't have an "exposure"), and
- FF is a fate factor.

The unit is PDF * year and it is aimed for to be calculated globally, as the authors argue that only this way, an irreversible extinction of species on a global level can be shown – like an extinction risk. A PDF value of 0.01 indicates that, under continued pressure (e.g., from land use), 1% of all species worldwide are at risk of extinction. Since there are typically time lags between environmental pressures and their ecological effects, the duration of the pressure strongly influences whether the full extent of the impact will materialize. Species do not undergo instantaneous global extinction following a change in pressure; for example, an increase in land occupation does not immediately cause species loss within the affected ecoregion but instead unfolds gradually over time. Consequently, the duration of exposure is explicitly incorporated into the unit of ecosystem impacts (PDF·yr). Thus, impact scores should be understood as representing an increase in global extinction risk over a defined exposure period rather than as an immediate measure of global species loss. (Verones et al. 2020a)

Exemplarily, damage to ecosystem quality induced by land stress is assessed. It is based on UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA (Koellner et al. 2013). There, land use is defined as land occupation (PDF/m²) and land transformation (PDF*years/m²). For calculating specific ecoregion (marginal and average) characterization factors, the countryside species-area relationships (SAR) from the Chaudhary et al. 2015 approach are used. Six land types (annual crops, permanent crops, pastures, urban, extensive forestry and intensive forestry) and five taxonomic groups (mammals, birds, reptiles, amphibians, vascular plants) are differentiated. As value-choices the method defines other ones than individualist, hierachist and egalitarian (Goedkoop et al. 2009, which are used in ReCiPe2016). LC-IMPACT provides four sets of CF: 1) all impacts, 100 years (which implies a 100 years time horizon and a high level of certainty for specific impacts), 2) all impacts, long-term, 3) certain impacts, 100 years, 4) certain impacts, long-term. In this study, only 1) is analysed. (Verones et al. 2020b)

LC-IMPACT modelled the ecosystem quality damage pathway from land use in four steps:

1. Creating local CFs by comparing the local species richness of a certain land use type with the reference situation and calculate the relative changes in species richness (according to de Baan 2013 and Koellner et al 2013) in the resolution of biomes.
2. Calculating regional CFs for 804 terrestrial ecoregions for five taxonomic groups and six land use types according to Koellner et al. 2013b by feeding local CFs into countryside SAR models and calculating the species extinction.

3. Weighted CFs are calculated by multiplying the regional CFs with vulnerability scores (VS) of each species for a specific region with a unit "global species eq. lost per unit of land occupied or transformed" for those 804 ecoregions. To avoid overrepresenting of one taxonomic group just because it's species rich, the contributions of a species is included relative to their species richness according to Verones et al. 2015 and the calculation method for VS is extracted from Verones et al. 2017 and 2019. The VS is a value between 0 and 1, implying a high threat for a value if 1 and a lower threat with a value close to 0. Information from IUCN, the red list and geographical range areas of species was taken to calculate a vulnerability score to represent that taxonomic groups do not all respond with the same level of vulnerability to environmental pressures. Additionally, plants and animals receive each a 50% share.
4. Final endpoint (global PDF) is calculated by aggregating the global CFs.

The final world average endpoints CFs of LC-IMPACT are displayed in Table 2.

Table 2: LC-IMPACT – World average endpoint CFs. Mean CFs along 2.5 & 97.5 percentile values for land occupation and transformation. (Verones et al. 2020b)

Characterization Factors		Annual crops	Permanent crops	Pasture	Urban	Extensive forestry	Intensive forestry
Occupation (PDF/m^2)	Mean	$2.1*10^{-15}$	$1.5*10^{-15}$	$1.3*10^{-15}$	$2.4*10^{-15}$	$3.7*10^{-16}$	$1.1*10^{-15}$
	2.5%	$-2.0*10^{-16}$	$-6.9*10^{-16}$	$-4.9*10^{-16}$	$2.7*10^{-17}$	$-6.3*10^{-16}$	$-7.1*10^{-16}$
	97.5%	$4.7*10^{-15}$	$4.9*10^{-15}$	$4.2*10^{-15}$	$4.9*10^{-15}$	$2.8*10^{-15}$	$4.1*10^{-15}$
Transformation Core ($PDF*year/m^2$)	Mean	$1.5*10^{-13}$	$1.1*10^{-13}$	$9.0*10^{-14}$	$1.7*10^{-13}$	$2.7*10^{-14}$	$7.8*10^{-14}$
	2.5%	$-3.2*10^{-14}$	$-8.9*10^{-14}$	$-7.8*10^{-14}$	$1.7*10^{-15}$	$-8.9*10^{-14}$	$-1.0*10^{-13}$
	97.5%	$3.6*10^{-13}$	$3.6*10^{-13}$	$3.2*10^{-13}$	$3.7*10^{-13}$	$2.1*10^{-13}$	$3.1*10^{-13}$
Transf. Extended ($PDF*year/m^2$)	Mean	$2.5*10^{-13}$	$1.8*10^{-13}$	$1.5*10^{-13}$	$2.9*10^{-13}$	$4.2*10^{-14}$	$1.1*10^{-13}$
	2.5%	$-3.0*10^{-14}$	$-8.8*10^{-14}$	$-7.7*10^{-14}$	$2.8*10^{-15}$	$-8.9*10^{-14}$	$-1.0*10^{-13}$
	97.5%	$6.6*10^{-13}$	$6.7*10^{-13}$	$5.9*10^{-13}$	$6.8*10^{-13}$	$3.9*10^{-13}$	$5.5*10^{-13}$

Overall integration of biodiversity levels and drivers

Of the three levels of biodiversity, only species diversity is addressed. It is a multi-indicator method and of the five main drivers of biodiversity are (partly) addressed: Climate change; land use / transformation and pollution through toxicity, eutrophication, and acidification. The drivers invasive alien species and direct exploitation of organisms are not addressed with this impact assessment method.

Exemplary data analysis with regard to land use indicator

For the calculation of CFs, a detailed species map with a resolution of 0.05°x0.05° was created with IUCN data and species maps from other authors. The IUCN offers geographic range sizes for many species, including spatial data compatible with geo information system (GIS) applications. With Matlab (Mathworks 2016) the map was created by overlaying geographical ranges of the relevant species with the number of species on the global grid, described in Verones et al. 2013. For vascular plants, a map of Kreft et al. (2007) resolution was used. The map could not be resampled to the Matlab map, as there were no species lists available for different classes & locations. To match the two maps, the authors aggregated the more detailed map to be overlaid with the map with lower resolution.

Species richness per ecoregion for all species groups were extracted from Olson et al. (2001), Kier et al. 2005 and WWF wildfinder database. Habitat areas and area per land use type for all 804 ecoregions stem from LADA and Anthrome maps (Ellis & Ramankutty 2010). Data for VS was used from IUCN and birdlife international databases. Regeneration times for land transformation CFs are derived from Curran et al. (2014).

Additionally, databases like GLOBIO (Alkamade et al. 2010) and the Swiss biodiversity monitoring (BDM 2004) were used. For local characterization factors, data from global reviews from de Baan et al. (2013) (for all land use types), Elshout et al. (2014) (for agricultural land) and Aronson et al. (2014) (for urban areas) were used. The spatial resolution for different impact categories is shown in Table 3.

Table 3: Spatial resolution for the different parts of the environmental mechanisms

environmental mechanism	Spatial resolution fate factor	Spatial resolution effect factor	Spatial resolution characterization factor
climate change (ecosystems)	none	none	none
climate change (human health)	none	none	none
stratospheric ozone depletion	none	none	none
ionising radiation	global values for air, freshwater, marine	none	global values for air, freshwater, marine
photochemical ozone depletion (ecosystems)	56 world regions (averages of base run of 1°x1°)	none	country level
photochemical ozone depletion (human health)	56 world regions (averages of base run of 1°x1°)	none	country level
particular matter formation	56 world regions (averages of base run of 1°x1°)	none	country level
terrestrial acidification	615'888 three dimensional compartments	2° x 2.5°	2° x 2.5°
freshwater eutrophication	0.5° x 0.5°	biogeographical habitats	0.5° x 0.5°
marine eutrophication	Country to large marine ecosystems (233 spatial units)	66 large marine ecosystems (5 climate zones)	Country to large marine ecosystems (233 spatial units)
freshwater ecotoxicity			sub-continental
human toxicity			sub-continental
marine ecotoxicity			sub-continental
terrestrial ecotoxicity			sub-continental
land stress	ecoregions	ecoregions	ecoregions
water stress (ecosystems)	more than 20'000 individual points	more than 20'000 individual points	0.05° x 0.05°
water stress (human health)	watersheds (11'000 units)	country level	watersheds (11'000 units)
mineral resources extraction	none		none

Exemplary regionalisation analysis with regard to land use indicator

LC-IMPACT covers global assessment for impact categories that have a global impact like climate change, stratospheric ozone depletion and mineral resources extraction. Impact categories that have an effect on the local level (for example land use) are modelled with spatial differentiation. Four spatial CFs are reported: Original "native", country averages, continental averages and global averages (for when the location of extraction/emission is not known). Whereof the resolution of the "native" CF depends from the specific impact category. LC-IMPACT refers to models from different other scientists like Olson et al. (2001), which states that a "native" resolution for water stress is (sub)watershed, for land stress it is ecoregions with similar ecological conditions. Aggregation to the country, continental, and global levels was carried out based on the locations where emissions or resource consumption are most likely to occur, using spatially explicit emission data specific to each impact category. In the case of land use, the relative area shares of ecoregions within each country or continent were applied as the basis for aggregation according to Olsen et al. (2001). (Verones et al. 2020a). For land use, 804 ecoregions are evaluating, covering the globe. The average values for countries and continents are given on the basis of the proportion of ecoregions within these areas. (Verones et al. 2020b)

Overall applicability & usage

LC-Impact can be used in LCA software tools and is therefore easily accessible for LCA practicioners. Within the funded project, several case studies were done which are accessible on

- Hauschild et al. 2016
- Núñez et al. 2016
- Ziegler et al. 2016
- Goedkoop et al. 2016
- Milà i Canals et al. 2016

Generally, LC-Impact provides

- Multi-indicator method with 11 midpoint and 3 endpoint indicators
- ecosystem quality covers partly biodiversity loss in PDFglobal * year, derived globally present species, which result a globally normalized PDF of species.
- three of the five drivers that are indirectly addressed via impact categories, but not comprehensively
- Original "native", country averages, continental averages and global CFs
- widely used in LCA software, as it is integrated in LCA tools
- data gaps: focuses on species level, lacks ecosystem and genetic diversity

4.4 Product Biodiversity Footprint

The Product Biodiversity Footprint (PBF) is a public-private research and development initiative launched in 2017 by I-Care & Consult, sited in Paris, France, and co-developed with Sayari, sited in Saint-Germain en Laye, France. It is a multi-indicator method, using an existing LCIA method of choice like LC-Impact to quantify three of the five main biodiversity drivers and additionally includes qualitative aspects for the remaining two biodiversity drivers. It is funded by the French Environmental Protection Agency (ADEME) together with three private partners: L'Oréal, Groupe Avril, and Kering. It is a multi-stakeholder project at French and international level including a steering committee of French agencies and ADEME, a scientific committee of AgroParisTech, National Natural History Museum, INRA, SCORE LCA, UN Environment, IRSTEA, and collaborative experts like IUCN, WWF, FAO, EC-JRC (TBC), CDC Biodiversité, Cambridge Institute for Sustainability Leadership and many more. (PBF 2025b)

The project's objective is to support biodiversity-conscious decision-making in product design (Asselin et al. 2019). The PBF project aims at developing a method and tool to quantify biodiversity aspects (species level) of a product along the life cycle stages. No document which reports their methodology is published (yet) which could be used to verify their claims. This method is neither publicly nor as a paid service available and it seems like the development has stopped. They have three targets to be achieved with their tool (PBF 2025a):

1. "Discriminating capacity": The total footprint of the product is calculated in an absolute value and the method shall be able to identify the product with a lower impact on biodiversity between different variants of one product. For long-term development, the developers want to ensure that different products or sectors at larger scale are able to be compared with this method.
2. "LCA ecosystem": The developers aim at integrating the method into the LCA world, meaning that it should comply to LCA framework and use LCA data.
3. "Large scope": All five biodiversity pressures (climate change, land use, pollution, invasive species, overexploitation of species) are planned to be assessable. Three of them through LCIA methods (climate change, land use, pollution) and two of them (invasive species, overexploitation) through a semi-quantitative approach with ecological data and a literature back-up (Asselin 2019). (PBF 2025a)

The projects method is visualized in Figure 6. At a user entry, the user shall be able to insert product foreground data and inventory, additionally information on practices and local information. This information is fed into the tool which integrates LCI data from e.g. ecoinvent, agribalyse and others in Module 1, which is the "Spatialized LCA Biodiversity layer". LCIA characterization factors are also added in Module 1 which are currently available in published LCA methodologies. The criteria is that it is a spatialized method and follows UNEP-SETAC guidelines – CFs from LC-IMPACT apply to these criteria (Asselin et al. 2019). Information from Module 1 goes into Module 2 and the product foreground data is fed into Module 3, a "Non LCA Biodiversity impact layer".

Both modules are supposed to be supplemented with product biodiversity data from certification schemes and additional biodiversity databases like IUCN, Predicts and others. Module 2 includes criteria and rules per land type (arable crops, perennial crops, grassland, mining, forest, urban, …) and or sector (livestock, transport, electricity, construction, …). Certification schemes with regard to land use type like FSC, Sustainable Rice Platform, RSPO, RTRS, Bonsucro, could be considered in this module. Module 3 includes qualitative aspects (not covered with LCA) for invasive species and species management for a statement on overexploitation (hunting, poaching, overfishing, pollinators reintroduction, monitoring endangered species). The resulting information is expressed as a map, quantitative (potential species lost global and regional) and qualitative indicators (score on each of the five biodiversity pressures). (PBF 2025a)

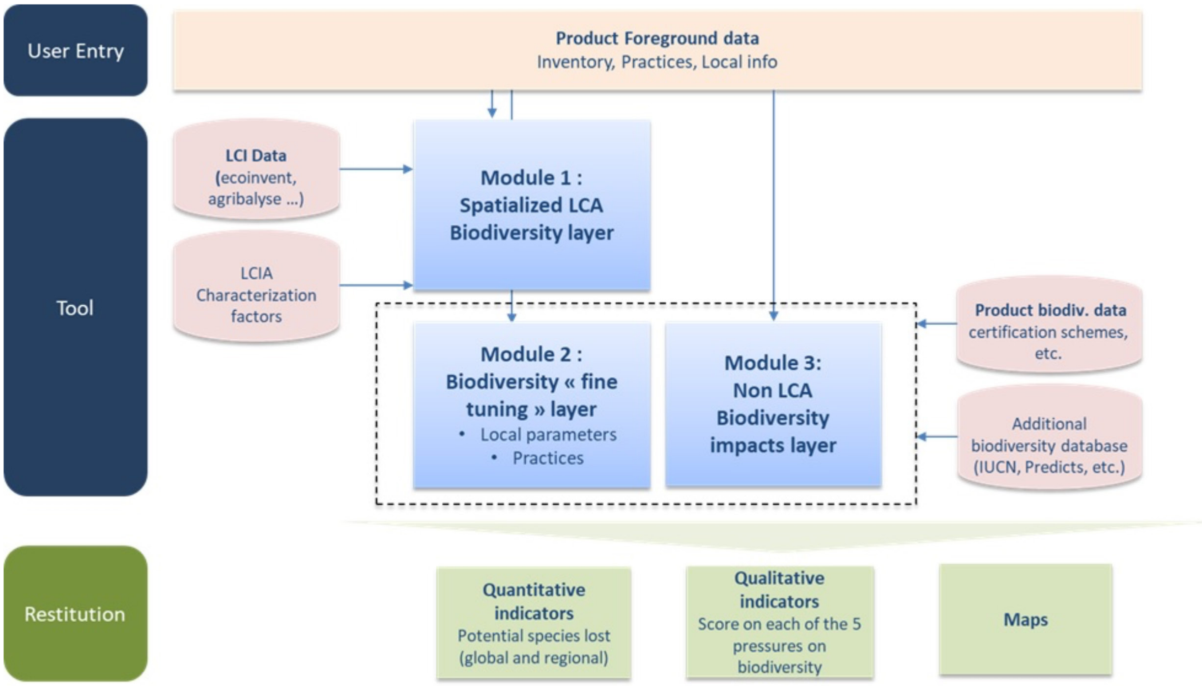

Figure 7: Product Biodiversity Footprint architecture (PBF 2025a)

Module 1 shall enable to show the hotspots of the products geographically along the value chain (PBF 2025a). In the example of L'Oréal, for Module 1, LC-Impact was chosen as LCIA method for several reasons. First of all, a spatialization was needed, which is provided by for example Impact World+, ReCiPe2016 or LC-Impact. ReCiPe2016 and Impact World+ have the same range of impact pathways, but ReCiPe2016 does not spatialize land occupation and transformation and Impact World+ does not use the UNEP-SETAC CFs for land use. On the other hand, uses LC-IMPACT the to that date latest impact pathways in LCIA spatialization and expresses biodiversity loss in PDF*year (Asselin et al. 2019).

Module 2 shall visualize benefits of a defined practice / location over different scenarios for one product (PBF 2025a). This should ensure, that also the agricultural practices are accounted for, which are not reported in LCI databases nor covered by the CFs of the LCIA method (Asselin et al. 2019).

Module 3 shall give a qualitative statement on invasive species and overexploitation (PBF 2025a). According to Asselin et al. (2019), semi-quantitative indicators are provided to assess these two drivers. Within this Module 3, also pressures, which are not covered with LCA are aimed to be addressed like "competition with threatened species" or "destruction of species of socio-cultural value". The level of impact is assessed qualitatively with two factors with a range from 1 to 6 or 7: level of impact and level of actions. (Asselin et al. 2019)

Overall integration of biodiversity levels and drivers

The method is neither publicly nor as a paid service available. At the time of research (September 25) it is not available which biodiversity levels will be integrated. Of the five drivers, it is aimed to integrate all of them. (PBF 2025a)

Data with focus on land use

The developers aim at integrating LCA databases, such as ecoinvent, agribalyse and biodiversity data such as certification schemes for biodiversity and IUCN, PREDICTS data. More specific information is not (yet) publicly available. (PBF 2025a)

Exemplary regionalisation analysis with regard to land use indicator

PBF aims at a regional and global assessment. (PBF 2025a)

Overall applicability & usage

The method is not yet available. The developers made three case studies, of which one is available for a fee in Asselin et al. 2019. (PBF 2025a)

Generally, PBF provides

- It is a method which aims to include the five drivers of biodiversity loss and different indicators, depending on the selected LCIA method.
- Only species level assessed.
- The biodiversity loss due to habitat change, pollution and climate change can be expressed in PDFregional * year. The two semi-quantitative indicators cannot be expressed with that unit, unless specific value choices are made.
- Method not yet publicly nor paid available
- data gaps: only species level addressed, not ecosystem and genetic level.

4.5 Biodiversity Impact Assessment+

Biodiversity Impact Assessment+ (BIA+) is a method developed by Lisa Winter in her phd thesis in 2018, at the TU Berlin in Germany, which relies on the biodiversity impact assessment (BIA) model from Lindner et al. (2014) (which is by date out of scope of this assessment). The BIA+ method aims at covering some shortcomings of earlier LCIA methods within the land use method. It is a single-indicator method and includes two core components: (1) Impact on Biodiversity Status (BS) as Impact Functions (IFs) within a major habitat type which were defined by WWF, and (2) a Habitat Factor (HF) that weights the biodiversity importance of those 14 major habitat types, see Table 4. Biodiversity is expressed with the following equation:

$$Biodiversity = HF * BS$$

The BS index integrates species richness, endemic species, grassland, and forest shares. Statistical analyses link BS to parameters such as soil pH, cultivated land, and temperature, generating 42 functions across habitats. The phd thesis provides one case study.

Table 4: BIA+ - Major habitat types (MHT) and related habitat factors (HF) (Winter et al. 2017)

MHT	HF
Tundra	0.63
Boreal Forests/Taiga	0.76
Deserts and Xeric Shrublands	1.02
Montane Grasslands and Shrublands	1.24
Tropical and Subtropical Grasslands, Savannas, and Shrublands	1.29
Temperate Conifer Forests	1.34
Temperate Grasslands, Savannas, and Shrublands	1.43
Flooded Grasslands and Savannas	1.43
Temperate Broadleaf and Mixed Forests	1.44
Tropical & Subtropical Moist Broadleaf Forests	1.46
Mediterranean Forests, Woodlands, and Scrub	1.53
Tropical and Subtropical Dry Broadleaf Forests	1.61
Tropical and Subtropical Coniferous Forests	1.72
Mangroves	1.82

HF = habit factor; MHT = major habitat type.

Lindner et al. (2014) was selected as base for the BIA+ method, because it includes species, ecosystem and genetic biodiversity, however, it includes only the land use impact on biodiversity. The BIA method relies on the UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services by Koellner et al. (2013) and is based on Michelsen (2008). Michelsen introduced that the quality of biodiversity in an area is based on its environmental conditions and the amount of possible biodiversity (location with high or low biodiversity) through a weighting factor. Lindner et al. (2014) formed an equation of biodiversity = ecoregion factor x biodiversity potential (BP) for a specific location. The ecoregion factor represents a weighting factor for a specific ecoregion and the biodiversity potential describes the state of biodiversity. Within the BIA method, a high resolution based on ecoregions is used. Each major habitat type consists of several ecoregions. The ecoregions were developed by WWF, which defined 827 ecoregions around the world. For each ecoregion, the ecoregion factor is calculated with species richness, ecoregion scarcity, normalized uniqueness of endemic species and the value of threat. Data from WWF wildfinder database was used to calculate this. The HF for every MHT is calculated with the sum of ecoregion factors existing in the specifc MHT multiplied with the area of that ecoregion in the MHT and divided through the area of the specific MHT, see following formula.

$$HF_{MHT} = \sum ecoregion\ factor_{MHT} * \frac{area_{Ecoregion\ in\ MHT}}{area_{MHT}}$$

For the definition of the biodiversity potential, expert judgements were consulted for the different ecoregions to define specific impact functions per midpoint impact category. Experts were asked to evaluate which parameters regarding land use are important for a specific ecoregion and to estimate the impact of those parameters. Winter assumes, that the scientists include all three levels of biodiversity within their judgements. Within her study, two examples are given to demonstrate the impact functions, however, Winter states, that more impact will need to be defined, which has not happened yet since then.

Overall integration of biodiversity levels and drivers

All of the three levels of biodiversity are addressed through expert judgements. It is a single-indicator method focusing on land use.

Exemplary data analysis with regard to land use indicator

The data stems from WWF wildfinder databases and expert interviews.

Exemplary regionalisation analysis with regard to land use indicator

The assessment is designed to be global in scope. Data for 827 ecoregions worldwide was grouped into 14 major habitat types. LCA inventory data is at country scale.

Overall applicability & usage

The BIA+ method has not been used within any other LCA study. The author states, that the thesis should be the basis for further development. Therefore, it is not widely used and it is not integrated in LCA softwares. One case study exists within the paper.

4.6 BioMAPS

BioMAPS is a methodology developed to account biodiversity with a specific focus on land-use related biodiversity risks. It is a single-indicator method. The method consists of three spatial scales (global, regional and local) which are incorporated into a single biodiversity risk score. The method has been developed by Fraunhofer Institute for Building Physics, Stuttgart, Germany, and combines models and data from biology, ecology and conservation. The three different spatial scales are calculated after each other, starting with the global biodiversity risk, followed by the local biodiversity risk and finally the regional biodiversity risk. The model specifically focusses on the pressure land use, however it also includes other pressures, for example pollution pressures related to nitrogen and pesticide use. The model covers the entire world and provides background data for each country and cell in the model. The method has been developed with a focus to be compatible with the LANCA method, a land use method applied in the Product Environmental Footprint, to enable easier inclusion of the method into existing LCIA methods and LCA software.

$$CF = BR_{global} + \frac{BR_{local,LUI}}{100} + BR_{regional,RDI}$$
$$PBR = CF * a * t$$

The global risk factor for biodiversity is calculated by providing information on the location of land use and includes factors accounting for the different organisational scales (ecosystems, species and genes) as well as their vulnerability and irreplaceability, based on the evaluation of 10 conservation schemes. The regional scale encompasses the landscape composition, which is described as the proportion of patches of all land use types and their intensities. The local level describes the land use type of the field or patch, which can include more specific information on management parameters or intensity values when available. Finally, the three spatial scales of biodiversity risk are combined and multiplied with the area and time to obtain the final biodiversity risk, according to the formulas below.

- CF is the characterization factor
- BRglobal is the Global biodiversity risk factor
- BRlocal, LUI is the local biodiversity risk factor depending on land use type and intensity
- BRregional, RDI is the regional biodiversity risk factor depending on landscape composition and intensities
- a is the area considered
- t the time considered and PBR the total potential biodiversity risk.

The overall methodological framework of BioMAPS comprises three different parts for the three spatial scales. For details on the three different spatial scales, see Annex 7.4. The calculation procedure of each of the three parts is in more detail following this summarized structure:

1. The global scale (BRglobal) includes the assessment of global biodiversity risk areas and creation of a unified biodiversity risk (UBR) map with different organizational biodiversity levels and conservation indicators. This is followed by a gap analysis of areas that are not covered by global conservation schemes. In the final step a regionalization of global risks with land use models for occupation and transformation is performed. This encompasses the calculation of the share of land use in risk areas, the proportion of risk areas per grid cell and the share of threatened, endemic and total species in non-risk areas (Jenkins Index). A global biodiversity risk factor of different land use types is obtained.

2. At the local scale, impact intervals are derived for each land use type and combined with management practices to obtain the local biodiversity risk (BRlocal,LUI). The local scale includes management parameters which determine the land use intensity (LUI), to assess where the actual land use intensity falls on the impact interval.
3. The regional scale assesses the biodiversity risks of the individual land use types within a landscape, by applying the LUI of the local scale to the different types of land use within the landscape. Combining this information with information on the presence of the land use types within the landscape enables the calculation of the biodiversity risks at regional level (BRregional,RDI).

BioMAPS proposes to use a land use nomenclature based on the flow properties that define a land use type. The proposed nomenclature seperates land use flows based on so-called flow properties such as land use type specific set of management parameters, land use intensity and its geolocation.
The first two levels of the land use flow nomenclature resemble those used by Chaudhary (Chaudhary & Brooks 2018), which are based on the land use impact model of the PREDICTS database. The nomenclature is extended by applying the land use model of Hurtt (Hurtt et al. 2011), which categorises 12 different land use classes and subclasses. To enhance the implemantion of the BioMAPS method in existing LCA software and the LANCA model, the nomenclature is matched to current ILCD land use flows. For more details, see the Annex (Chapter 7.4) or the methodological describption (Maier 2023).

Overall integration of biodiversity levels and drivers

All of the three levels of biodiversity are addressed through the use of data from conservation schemes which cover genetic, species and ecosystem biodiversity at the global scale. At regional and local scale, indicators related to species and ecosystem biodiversity are taken into account. The BioMAPS method mainly focusses on habitat change as driver of biodiversity loss. The BioMAPS method explicitly states that it does not include climate change as part of the method, and pollution and alien species are solely covered through management parameters at the local level. Pollution is covered at the local level through the inclusion of management parameters in the land use intensity calculation. Management parameters, for various land use types, related to pollution include synthetic fertilizer use, pesticide use, fertilizer use on pastures, pesticide use in grasslands, light pollution and population density. Overexploitation for various land use types is covered through (management) parameters such as crop rotation, mechanization, mowing, livestock intensity, population density, anti-poaching, wood harvesting rates and tree age. Invasive species are considered at the local level through the parameter human population density, and at the regional (landscape) level through management parameters such as set-aside areas and the clearing of vegetation, though these play a small role in the overall assessment method.

Exemplary data analysis with regard to land use indicator

The BioMAPS method combines data from various sources at the global, regional and local level.

The global level combines multiple biodiversity conservation schemes to generate the global risks maps. It includes data from the the following sources: Biodiversity Hotspot, Key Biodiversity Areas, High Biodiversity Areas, Last of the Wild, Intact Forest Landscapes, Important Bird Areas, Global 200 Ecoregions, Centers of Plant Diversity, Alliance for Zero Extinction and Evolutionarily Distinct and Globally Endangered. Areas not covered by any of the conservation schemes mentioned above are filled with data obtained from Jenkins et al (2013). Data for global land occupation is obtained from the land use model of Hurtt et al. (2011) and is stored in the Network Common Data Format, enabling the linking between the biodiversity risk and land use type.

For the local scale, the BioMAPS methods uses data obtained from Newbold et al. (2015 & 2016) which is based on the PREDICTS database (Hudson et al. 2014), to evaluate the impact of different types of land use based on biodiversity indicators. This enables the calculation of the local biodiversity risk index, as well as characterization factors for occupation and transformation of land use types. Since the local biodiversity risk index provides intervals, management parameters are used to determine the land use intensity, by using data obtained from the Conservation Evidence Database to assess the effectiveness of management activities. Data for included management activities is obtained from various sources, such as Hurtt et al. for fertilizer application, crop rotation, wood harvesting rates, biomass density and tree age, FAO (FAOstat & various publications) for pesticide application, mowing intensity, mechanization and manure application on pastures, the work of Gilbert et al. (2018) on livestock intensity, data from UNECE Transport division on traffic intensity (UNECE 2019), Elvidge et al for global sealing data (Elvidge et al. 2007), Falchi et al for light pollution (Falchi et al. 2016), CIESIN for population density (CIESIN 2005), Forest Europe for deadwood (Forest Europe 2011) and UNEP-WCMC & IUCN for set-aside areas in forests (UNEP-WCMC and IUCN 2019). It must be noted that global data is not available for every management activity proposed in the BioMAPS method.

The regional scale calculations is based on data obtained from Hurtt et al. (2011) which enables the calculation of types of land use present in a region using the BioMAPS method to account for local biodiversity risks.

Exemplary regionalisation analysis with regard to land use indicator

The BioMAPS method can be applied to quantify biodiversity risks on global, regional and local level, The method can be applied at country level as well. As such, various spatial scales can be assessed. The resolution of the grid cell used in the unified biodiversity risk map is 0,25° x 0,25°, similar to Hurtt et al. (2011)

Overall applicability & usage

To apply the methodology in an LCA, the following steps are required:

1. Mapping of land use processes in all lifecycle phases,
2. Analyse land use type specific impacts on biodiversity if no primary data on management parameters or land use intensity is available,
3. Assessment of land use intensity or management parameters on biodiversity, either through average values or primary data,
4. Assess the landscape scale by using country, grid cell or primary data and finally
5. Calculate the potential biodiversity risk by summing the global, regional and local scale and multiplying by the area and time.

The steps are visualized in the diagram in Annex 7.4. Sphera has implemented the method in its Managed LCA Content (Pauer 2023). The methodology applies the same land use flow nomenclature as the ILCD land use flows to facilitate integration in existing LCA software and the LANCA model, which applies the same ILCD land use flow nomenclature. Within the methodology description, a case study is provided on the biodiversity impact of different energy carriers for transportation with respect to their land use occupation. In a telephone call with the EF developers in September 2025, it was stated that BioMAPS will be recommended for inclusion in the PEF methodology.

Generally, BioMAPS provides

A biodiversity assessment method applicable at global, regional, national and local scale which can be used both as background data source and foreground modelling, provided site-specific information is available. The single-indicator method is compatible with the LANCA method for easier integration of land use related biodiversity impacts into commonly applied LCA methodologies and software. The method encompasses a wide variety of biodiversity related data and indicators to assess biodiversity impacts of production value chains.

4.7 Global Extiction Potential

The global extinction potential (GEP) has been proposed by Kuipers et al. (2019) and has been further developed by Verones et al. (2022). It is a single-indicator method, which can be applied to several indicators. The approach builds on the commonly used indicator PDF (Potential Disappeared Fraction of species), to alleviate limitation of the indicator (PDF) across various spatio-temporal scales. PDF represents the potential decline in species richness relative to reference conditions. It is expressed from 0 to 1, with 0 meaning that all original species are still present, whereas 1 means all original species have disappeared. The regional loss of a species which occurs in many regions does not result in a global extinction, whereas the regional loss of a species present in only one region results in the extincition of said species. The GEP relies on data of the species range size, global conservation status and species richness to approximate the extent to which regional species loss contribute to global species loss, by scaling from regional to global extinction. This scaling factor is called the global extinction probability and is calculated by applying the formula below.

$$GEP_{g,j} = \frac{\sum_s \frac{\sum_i A_{s,j,i} \bullet O_{s,j,i} \bullet TL_s}{\sum_{j,i} A_{s,j,i} \bullet O_{s,j,i}}}{\sum_s TL_s}$$

In the formula above,

- the GEPg,j is the global extinction probability of a species group (g) in a region (j), where the region can be defined in various ways (country, ecoregion, grid cell).
- Where As,j,I is the part of the range area of a species (s, which belongs to a higher species group (g)), in a region (j) and grid cell (i) at a resolution of 0,5°.
- The occurance-weight, Os,j,I, which is a dimensionless number representing the occurance certainty of the species in the region and grid cell and
- the threatlevel (TLs) of the species based on the IUCN red list.

The equation is structured so that the GEP for regions which are larger than the individual grid cells, are the sum of the grid cell level GEPs. Furthermore, the GEP is defined such that if it is summed over all regions, the GEP becomes one, meaning that if all species in the group are lost in all regions, the species group becomes globally extinct. Verones et al. (2022) provide an example in which the GEP is calculated for a hypothetical ecoregion to illustrate the calculation procedure. The procedure starts with the calculation of the total occurrence-weighted area of a species in a region, by multiplying the grid cell area with the relative occurance certainty. The second step in the procedure divides the occurrence-weighted area by the total number of the species in all regions. The third step multiplies the fraction of occurance per grid cell with the threat level per cell. The fourth step aggregates the values per species and in the final, the values are normalised to the sum of all threat levels, to ensure that the sum of all GEP values is equal to 1.

The values used for occurrence certainty per grid cell and species have been adopted from Kuipers et al. (2019), which have been taken from Montesino Pouzols et al. (2014). In this approach, extant species are assigned a value of 1, whereas probably extant and possibly extant species are assigned 0,5. Possibly extinct species are assigned 0,1 and extinct and possibly extinct species are assigned 0. To convert threat levels into numbers, various approaches are discussed (linear, logarithmic and categorical approaches) which aim to convert the IUCN Red List threat level categories (extinct, critically endangered, endangered, vulnerable, lower risk, near-threatened, least concern and data deficient) into values between 0 and 1. The approach chosen is a value choice, where choices with a large difference between the highest and lowest value of threat level result in a larger emphasis being put on areas with high species richness and many endemic species.

The approach outlined above has been applied for three ecosystem types (terrestrial, freshwater and marine). Within the terrestrial ecosystem, 5 species groups have been included (vascular plants, birds, reptiles, amphibians and mammals). For freshwater ecosystems, 14 species groups are included (freshwater plants, birds, reptiles, amphibians, mammals, freshwater fish, crabs, crayfish, dragonflies and damselflies, true shrimps, molluscs, fungi, branchiopods and clitellates). Marine ecosystems include 8 species groups (seagrasses, mammals, reptiles, ray-finned fishes, cartilaginous fishes, lobster, sea cucumbers and stony corals). The data has been obtained from the IUCN, extended with data obtained from Barbarossa et al. (2021) for freshwater fishes and a dataset from Borgelt et al. (2022) for terrestrial vascular plants. As can be seen from the data sources, most of the approach relates to the species level of biodiversity. The results of the GEPs for the species are provided based on global maps, where a high GEP may indicate the presence of many endangered species (according to the IUCN red list), species with a small range (endemic species) or both. Since the absolute number of species is irrelevant, the GEP shows species communities at elevated risk. As shown in the equation above, the results can be aggregated per ecoregion or per country, enabling the extension of LCIA methods relying on PDF indicators. Verones et al. (2022) compare the GEP calculated with the ICUN Range-size Rarity metric, showing similar patterns, while the GEP provides more regional differentiation due to the inclusion of the threatlevel. Compared to the initial work of Kuipers, the Verones extended the method to include more species and a higher cumulative range area.

In terms of applicability, two types of impact category indicators are identified where the GEP can be used. The first type encompasses CFs for impact categories corresponding to individual species groups (i.e. separate characterisation factors for terrestrial mammels, birds etc.). The second type encompasses CFs which include several species groups combined (for example fresh water ecotoxicity where freshwater fish and gastropods are condered together). For the latter approach, it means that all available species included in the GEP for the group are included in the calculation of the characterisation factor, even when the individual species used to determine the GEP and species sensitivity distribution do not match. In this situation, the species included are used as proxies. Furthermore, to apply the GEP, it is important that the GEP is aggregated to the same spatial level as the corresponding characterisation factor, before multiplication with the characterisation factor (Verones et al. 2022).

Verones et al. (2022) highlight some of the limitations and uncertainties to the approach, which include the difficulty in comparing terrestrial and aquatic ecosystems as aquatic ecosystems contain a third dimension. The third dimension may be relatively small in freshwater ecosystems, due to limited depth, and the high importance of coastal regions for marine ecosystems. Nonetheless, limited data availability on deep marine species presents a data limitation. Moreover, in general, the approach is limited by availability of underlying biodiversity data, meaning that species for which data is available, act as proxy for those for which it is not. Updating the approach when such data becomes available presents a way to mitigate this limitation. Furthermore, biases in available biodiversity data are propagated to the GEP, for example the characterisation factors may be biased towards more sensitive species. Moreover, the approach based on the classification in taxonomic groups implicitly assume similar responses to pressures within the taxonomic group, whereas there may not be a correlation between the response of the species within the group to the pressures. The GEP approach does not include all levels of biodiversity as it lacks information on the genetic as well as the functional ecosystems level (i.e. the interaction between various species within an ecosystem).

The authors stress that to overcome some of these limitations, it may be necessary to use multiple indicators to adequately depict the impact on biodiversity. Moreover, to aid interpretation, the authors recommend evaluating the impact on the biodiversity at both a global as well as a regional level and the separate reporting of impacts on different ecosystems, as the ecosystems are very different and can result in different interpretations. For example, the impact may be very high on the local functioning of the ecosystem, whereas the global effect on biodiversity is limited. Similarly, impacts on freshwater ecosystems may be different compared to terrestrial ecosystems.

Overall integration of biodiversity levels and drivers

The GEP provides information on species level of biodiversity, without considering gentic and ecosystems biodiversity. It could be argued that some aspects of ecosystems biodiversity are included as the GEP determines the distribution of species over the world followed by an aggregation of all species present in a specific region. The drivers covered are not explicitly stated as it can be applied to any characterisation factor.

Exemplary data analysis with regard to land use indicator

The data stems from IUCN Red list (spatial ranges, threat categories, occurrence certainty), Barbarossa et al. (2021), Borgelt et al. (2022) The resolution is 0.5° grid cells, which are aggregated to larger scales when needed. 98,212 species across 20 species groups for terrestrial, freshwater and marine ecosystems are included. Below is a table which provides an overview of the species groups included in the GEP.

Table 5: Species groups included in the GEP calculation (Verones et al. 2022)

Ecosystem type	Species group (common name)	Species group (scientific name)	Taxonomic rank	Phylum/Division/Kingdom
Terrestrial	Vascular plants	Tracheophyta	Division	Tracheophyta
	Birds	Aves	Class	Chordata
	Reptiles	Reptilia	Class	Chordata
	Amphibians	Amphibia	Class	Chordata
	Mammals	Mammalia	Class	Chordata
Freshwater	Freshwater plants	Tracheophyta	Division	Tracheophyta
	Birds	Aves	Class	Chordata
	Reptiles	Reptilia	Class	Chordata
	Amphibians	Amphibia	Class	Chordata
	Mammals	Mammalia	Class	Chordata
	Freshwater fishes	Osteichthyes	Superclass	Chordata
	Crabs	Brachyura	Infraorder	Arthropoda
	Crayfishes	Astacoidea and Parastacoidea	Superfamilies	Arthropoda
	Dragonflies and damselflies	Odonata	Order	Arthropoda
	True shrimps	Caridea	Infraorder	Arthropoda
	Molluscs	Mollusca	Phylum	Mollusca
	Fungi	Agaricomycetes, Lecanoromycetes	Class	Fungi
	Branchiopods	Branchiopoda	Class	Arthropoda
	Clitellates	Clitellata	Class	Annelida
Marine	Seagrasses	Alismatales	Order	Tracheophyta
	Mammals	Mammalia	Class	Chordata
	Reptiles	Reptilia	Class	Chordata
	Ray-finned fishes	Actinopterygii	Class	Chordata
	Cartilaginous fishes	Chondrichthyes	Class	Chordata
	Lobsters	Nephropidae	Family	Arthropoda
	Sea cucumbers	Holothuroidea	Class	Echinodermata
	Stony corals	Scleractinia	Order	Cnidaria

Exemplary regionalisation analysis with regard to land use indicator

It quantifies biodiversity impacts through Global Extinction Potential and scales local species loss to global extinction risk. It includes local loss and global loss, as the GEP provides a scaling factor that translates local Potentially Disappeared Fraction of species (PDF) into global extinction probabilities. The method includes different spatial resolutions like 5.5 km^2 grid cells, ecoregions, watersheds, countries and global averages.

Overall applicability & usage

Not yet available in standard LCA software packages, but it is possible to integrate it and recommended for the future to develop standard packages. The GEP is used in methods like Impact World+ and GLAM method and has been worked with already in different studies from Francesca Verones:

- Kuipers et al. 2019
- Dorber et al. 2019
- Kuipers et al. 2021a
- Kuipers et al. 2021b

Generally, GEP provides

- GEPs for impact categories that are species group specific or contain a mixture of species
- Application to any CFs included in the ecosystems quality AoP at multitude of scales (native scale of CF, country level)
- Method to translate local impacts to global extinction risks
- GEPs are based on a large variety of species

4.8 UNEP-GLAM

The Global Guidance on Environmental Life Cycle Impact Assessment Indicators (GLAM) is an initiative under the United Nations Environment Programme (UNEP) Life Cycle Initiative, launched in 2013 with the aim of establishing a globally consistent and comprehensive framework for environmental life cycle impact assessment (LCIA). It is a multi-indicator method. Its purpose is to strengthen international consensus on environmental indicators and CFs by recommending specific CFs, ensuring that life cycle assessment (LCA) studies around the world become more reliable and comparable. Over more than a decade, GLAM has been developed in three phases, with contributions from a wide range of stakeholders, including LCIA method developers, practitioners, governments, international organizations, NGOs, academia, and industry representatives. The first phase (2013–2016) addressed issues such as greenhouse gas emissions, climate change, particulate matter, water use and scarcity, and land use impacts on biodiversity. The second phase (2017–2019) expanded the scope to include acidification, eutrophication, human toxicity, mineral resource use, soil quality, and ecotoxicity. The third phase (2019 – 2024) culminated in the development of a comprehensive, consistent, and global LCIA method, including classification, midpoint and endpoint characterization, normalization, and weighting factors (LCI 2025). The outcome of this long development process was the official launch of GLAM 1.0.2024.10 at the SETAC Europe 26th LCA Symposium in Gothenburg in October 2024. This milestone is developed through an extensive consensus-driven process involving over 200 experts. Building on workshops held in 2016, 2018, and subsequent years, the method was refined through public consultations, beta testing, and expert reviews, ensuring robustness and global applicability. The approach integrates consistent classification, normalization, and weighting schemes, enabling comparisons of environmental impacts across regions and facilitating implementation in LCA software starting in 2025. The GLAM method contains three Areas of Protection (AoPs):

1. ecosystem quality,
2. human health, and
3. socio-economic assets.

The AoP Ecosystem quality at endpoint level, expressed in PDF, focuses on loss in species richness and therefore covers biodiversity aspects, harmonizing previous GLAM recommendations on land and water use, eutrophication, ecotoxicity, acidification, climate change, and microplastics. For all categories, GLAM applies a consistent normalization and weighting framework. Global normalization inventories have been established, while weighting factors were derived from a large-scale international survey of more than 3,000 citizens, reflecting both absolute and population-adjusted perspectives. This allows practitioners to consistently compare impacts across different impact categories and aggregate results further to receive a total damage for each AoP, when needed. (LifeCycleInitiative 2025, SimaPro 2024)

A working group within the GLAM project examined the impacts of land use and created new characterisation factors that integrate two recent advances in the field: land use intensity and the spatial effect of land fragmentation. Compared with earlier models, the underlying datasets used for parameterisation have also been updated. The resulting characterisation factors address five taxonomic groups (plants, amphibians, birds, mammals, and reptiles) across five land use categories (cropland, pasture, plantations, managed forests, and urban areas), each considered at three intensity levels (minimal, light, and intensive), see Figure 7. These factors are provided at both the terrestrial ecoregion and national scales (Scherer et al. 2023). Similarly, new models were developed for terrestrial acidification, freshwater and marine eutrophication, microplastics, and human toxicity within GLAM.

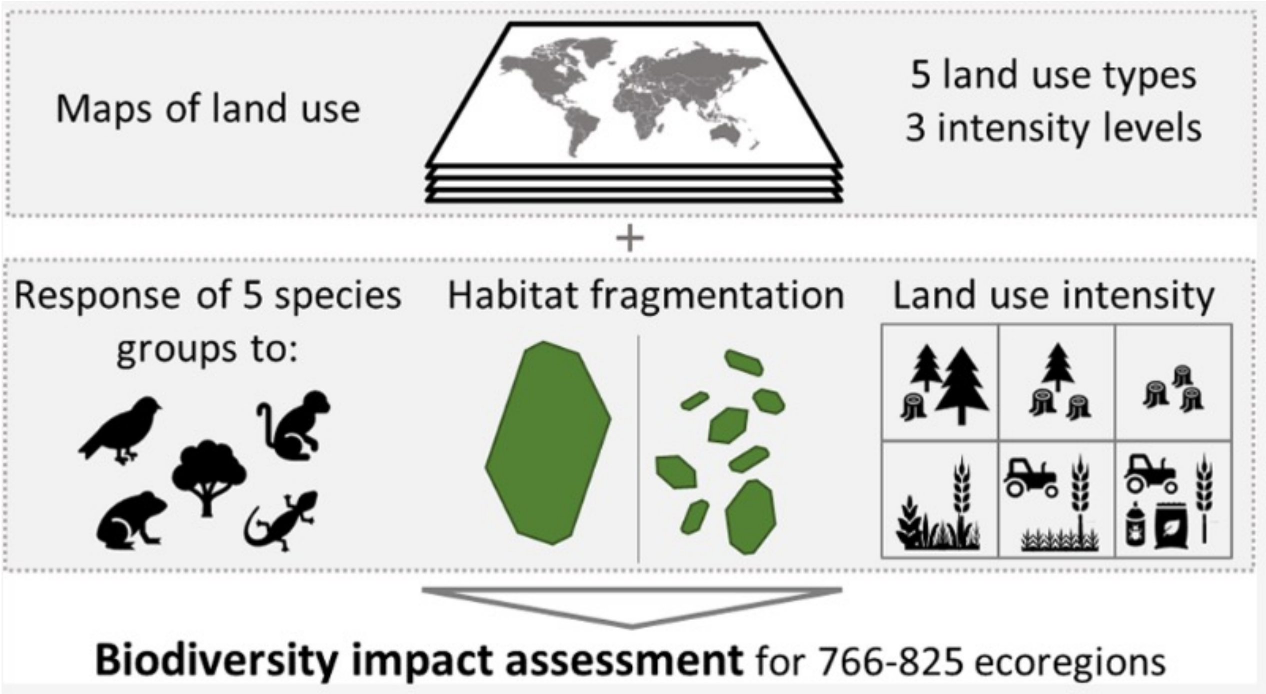

Figure 8: Data overview for land use intensity and fragementation from Scherer et al. 2023

According to Scherer et al. 2023, land use intensity describes how intensely the land is used (land use types e.g. cropland, pasture, plantations) and land fragmentation describes the physical breakup of habitats. To receive land use specific CFs (effect per area), the species-habitat relationships were build to estimate the relative species loss (expressed in PDF) for land occupation (expressed in PDF*yr) and land transformation (expressed in PDF * yr/m²) (called relaxation in the ReCiPe method) with a regeneration time t, all considering a specific land use type and intensity.

To obtain global PDFs (e.g. relative species extinctions), the regional CFs are combined with corresponding GEPs. The PDFs represent potential long-term relative species losses under sustained land-use activities; they therefore extend beyond immediate losses by incorporating extinction and extirpation debts. Habitat fragmentation is assessed using the Equivalent Connected Area (ECA) model. The ECA represents the size of a single, contiguous habitat patch that would provide the same probability of connectivity as the actual, potentially fragmented habitat pattern. See the original paper for the exact calculation of the CFs. (Scherer et al. 2023)

Overall integration of biodiversity levels and drivers

Of the three levels of biodiversity, only species diversity is addressed through the pathways. It is a multi-indicator method and of the five main drivers of biodiversity, three are (partly) assessed: global warming (climate change), land use and pollution through ecotoxicity, eutrophication and acidification. Additionally, water use and microplastic influence are addressed. The drivers invasive alien species and direct exploitation of organisms are not addressed with this impact assessment method.

Exemplary data analysis with regard to land use indicator

For plants, the model used local monitoring and experimental data compiled by Gallego-Zamorano et al. (2022) to estimate changes in species richness across land-use types and intensities. Plant dispersal distances were derived from species distributions (based on Maxent predictions by Borgelt et al. (2022), with regression models from Tamme et al. (2014) to estimate maximum dispersal ranges.

For vertebrates, two main sources were used: the PREDICTS database (which compiles biodiversity responses to land-use across the globe) and a meta-analysis on managed forests by Chaudhary et al. (2016). Vertebrate dispersal distances were estimated from body mass data in the EltonTraits database, while amphibians and reptiles were assigned fixed dispersal values. Global extinction probabilities for vertebrates were again drawn from Verones et al. (2022).

For land use mapping, the authors used HILDA+ (Historic Land Dynamics Assessment) as a harmonized global land-use dataset, supplemented by information on irrigation (Mehta et al. (2022)), fertilizer use, pasture data from GLOBIO4, plantation data from Lesiv et al. and Descals et al., managed forest loss (Potapov et al. (2022)), and urban area maps from the Global Human Settlement data.

Exemplary regionalisation analysis with regard to land use indicator

The CFs of the GLAM-method are derived from the work of different scientists. They include CFs at a native and country-level for impact categories that are effected by regions, for example freshwater eutrophication, water consumption and land use and global-level CFs for impact categories that are effected by global scale like climate change.

Specifically for land use, the method provides land-use and intensity-specific CFs for 825 ecoregions, five species groups and five land-use types (cropland, pasture, plantations, managed forests, urban), across three intensity levels. Therefore, it is regionally detailed, spatially explicit by land use types, intensity and geography.

Overall applicability & usage

According to GLAM, it is aimed to be included in LCA software tools starting from 2026 onwards (personal communication) as the method in its formatting is compatible with the tools. The method files are available free of charge at the Life Cycle Initiative website. They can be implemented by the users by downloading the method files and importing them into the software. This requires active involvement. It is used in several very recent studies like:

- Coelho et al. 2025
- Savallampi et al. 2025
- Fernandes et al. 2025

Generally, UNEP-GLAM method provides

- Multi-indicator method with 22 midpoint impact categories and 3 endpoint indicators
- ecosystem quality, which is the endpoint indicator that partly covers biodiversity loss in PDF * year, derived from nine midpoint indicators
- three of the five drivers that are indirectly addressed via impact categories, but not comprehensively
- global generic CFs, ecoregion-level & country-level CFs for some impact categories

- Aimed to be widely used in LCA software. But not yet integrated. Can be added manually by the practicioner.
- data gaps: focuses on species level (therefore high uncertainty), lacks ecosystem and genetic diversity. Invertebrates are not covered. Spatial uncertainties due to aggregation from ecoregions to countries or globe.

4.9 Biodiversity Value Increment

The Biodiversity Value Increment (BVI) method is a single-indicator method developed by Lindner et al. 2019/2021. The goal is to provide an impact assessment method for assessing biodiversity with LCA through quantification of potential impacts of land use on biodiversity. The method is based on UNEP-SETAC guidelines and includes land occupation and transformation in its concept. Additionally, the BVI method is based on the assumption that human-influenced areas, such as agricultural land, can still serve as habitats for a wide range of plant and animal species. The quality of the area is reflected by its condition and the better the condition of the area, the greater its biodiversity potential. The condition of this land (and so the habitat) is affected by any usage like tillage or the use of fertilizers or pesticides. Also structural elements that effect the shape of the landscape are influencing biodiversity. The parameters are used for the impact assessment. (Lindner et al. 2019)

The authors propose a biodiversity impact assessment method that unifies different existing approaches into a single framework. It combines the fuzzy framework developed by Lindner et al. (2021), which provides a fine-grained calculation structure but does not clearly define the actual biodiversity value, with the hemeroby concept by Fehrenbach et al. (2015), which equates naturalness with high biodiversity value but only offers a rough calculation model. In addition, it incorporates the framework introduced by Maier et al. (2019), which integrates regional weighting factors, fixed intervals for each land use type, and specific management parameters. The method presented here builds upon this foundation, aiming to meet the diverse requirements of stakeholders and address existing research gaps. To this end, it establishes a mathematical structure for biodiversity assessment, which is explained below. A quality indicator (Q) is assessed for a specific piece of land. Whereof input data are properties of the land that is assessed like management parameters. The calculation involves several steps:

1. Parameter level: Each management parameter input (x) (e.g., field size, fertilization intensity) is transformed into a biodiversity contribution function y(x). Differentiation between biomes and ecoregions and practices (land use classes and management parameters) is possible. Land use type levels were provided by Fehrenbach et al.
2. Criteria level: The biodiversity contributions are aggregated into criteria (e.g., soil conservation, structural diversity).
3. Land-use class value (BVLU): Criteria are weighted and summed for each land-use class (arable, pasture, forest, urban). Each land use class receives a minimum and miximum biodiversity value.
4. Local biodiversity value (BVloc): BVLU is fitted (normalized) into the interval of land-use-specific minimum and maximum biodiversity values.
5. Global biodiversity value (BVglo): BVloc is multiplied by the ecoregion factor, which weights biodiversity importance globally. Each of the more than 800 ecoregions is assigned an ecoregion factor, since different regions have different levels of biodiversity. This weighting is particularly relevant in global value chains. The resulting BVglo is expected to become the Q value for further use in the land use framework. The final unit is the Biodiversity Value Increment (BVI), an artificial comparative unit.

For more information, see Lindner et al. 2019.

Overall integration of biodiversity levels and drivers

The approach does not explicitly model each level separately, but it relies on naturalness (hemeroby) as a proxy, which strongly emphasizes the ecosystem level. The method focuses mainly on habitat change through land use and land use intensity, which is considered the dominant driver. Other drivers (climate change, invasive species, overexploitation, pollution) are not integrated into the calculation framework. However, pollution through pesticide and fertilizer use is included through management parameters regulations. The authors explicitly note that the method is designed for land use-related impacts only. (Lindner et al. 2019)

Exemplary data analysis with regard to land use indicator

The method uses a mix of literature-based indicators and secondary datasets:

- Hemeroby levels and management parameters (soil treatment, field size, fertilization, pest control, etc.) are adapted from ecological and forestry studies (e.g., Westphal & Sturm 1999, Fehrenbach et al. 2015, Brentrup et al. 2002).
- Threshold values for parameters come from regulations and ecological guidelines (e.g., Austrian agricultural directive).
- Global datasets for ecoregion factors:
  - Grassland and forest share (Winter et al. 2017)
  - Wetlands (Ramsar Convention Secretariat)
  - Global extinction probabilities (Kuipers et al. 2019)
  - Roadless areas (Ibisch et al. 2016)

Exemplary regionalisation analysis with regard to land use indicator

The framework integrates both local and global perspectives:

- Local biodiversity value (BVlocal): calculated for specific land-use practices using management parameters and criteria.
- Global biodiversity value (BVglobal): BVlocal is multiplied by an ecoregion factor to account for regional/ global significance of biodiversity.

The ecoregion factor incorporates global distribution of habitats (grassland, wetlands, forests), extinction probabilities, and roadless areas, covering 744 terrestrial ecoregions worldwide (data from Olson et al. 2001 and others). (Lindner et al. 2019) The characterisation factors are calculated for land occupation flows for three LCA databases (Agribalyse 3.1.1, ecoinvent 3.10 and Sphera LCA For Experts). The CF are applicable at global and country level, not at regional level. They include land use intensity and location. (Quandt et al. 2025)

Overall applicability & usage

According to Quandt et al. (2025) the CFs are available in LCA Software packages for OpenLCA 2.1.0 and Sphera LCA For Experts. Conversion plugins for OpenLCA exist which facilitate the integration of data into SimaPro. The authors did some case studies with the method, like the one available within Lindner et al. 2019 and other application papers like Lindner et al. (2022), „BVI appliqué à AGRIBALYSE" and Quandt et al. (2025).

Generally, BVI provides

- Single-indicator method: Mainly land use, as pesticide and fertiliser seem included in management parameters
- Biodiversity expressed as BVI (global biodiversity value, an artificial comparative unit)
- CFs available at global and country scale
- CFs available in LCA tools
- data gaps: focuses only on land use, lacks all other drivers. Lacks species and genetic level

5 Comparison of all methods

In this section, the above described methods are compared according to the criteria shown in the introduction: Overall integration of biodiversity levels and drivers; Exemplary data analysis; Exemplary regionalisation analysis; Overall applicability & usage – e.g., usage in software tools like Simapro / sphere & list of reference, where the method already has been applied and general aspects. Additionally reported, when provided by the method, are;

- category of method,
- number of impact categories related to biodiversity,
- followed LCA framework with regard to land use indicator,
- data gaps,
- unit of biodiversity loss and
- literature cited

The comparison of all evaluated methods is reported in Table 6.

None of the investigated approaches fully and simultaneously address all three levels of biodiversity and all five drivers. The investigated methods can be categorized into single-indicator and multi-indicator methods. Whereas, the single-indicator methods BIA+, BVI and BioMAPS are dedicated methods to assess biodiversity via the indicator land use. The GEP is a scaling method that can be applied to various indicators. The multi-indicator methods (ReCiPe2016, LC-IMPACT, IMPACT World+, GEP, UNEP-GLAM) include the biodiversity loss drivers land use, climate change and pollution. They also include additional pressures like water use, GHG, toxic, acidifying, nutrient and other air emissions, relevant for biodiversity assessment, and emissions in water and soil that mostly are included in characterisation factors. Invasive species, overexploitation, genetic or ecosystem level are usually not covered. The Product Biodiversity Footprint is a multi-indicator method using an LCIA method for land use, climate change and pollution and using a semi-quantiative way to address the other two drivers overexploitation and invasive species.

Many of the methods rely on similar or same impact categories with the same models and data. This can be seen exemplarily with land use. Most of the methods are based on UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA, based on Koellner et al. (2013). Literature that is often cited is de Baan et al. (2013), Elshout et al. 2014. Köllner et al. 2007, Curran et al. 2014 and Olson et a. 2001, to name some. Most of the methods provide CFs at local and global level. Many use ecoregions as spatial resolution and derive their data from GLOBIO3 (ReCiPe2016, LC-IMPACT) and GLOBIO4 (GLAM), WWF wildfinder database, Biodiversity Monitoring Switzerland, IUCN data / Red list, birdlife international databases, PREDICTS database and HILDA. Nevertheless, data gaps exist, as data is not available for all taxonomic groups. Therefore, even though if the methods claim to cover land use, it is only covered for the data that is available (which is not available for all taxonomic groups). This implies that the biodiversity pressure of exemplarily land use is not fully covered but only parts of it. Most of the methods rely on Species Richness or the Potentially Disappeared Fraction (PDF) as proxy indicators of “biodiversity loss” over time.

- ReCiPe2016 was developed in 2016 and is a widely used multi-indicator LCIA method with midpoint and endpoint categories. Biodiversity aspects are only partially covered by this method, with a focus on species diversity. It provides global and local CFs, depending on the impact category and its cause-effect pathways and covers climate change, parts of land use and pollution. The CFs are provided from literature models.
- IMPACT World+ was developed in 2019 and is a globally regionalized multi-indicator LCIA method. It provides spatially differentiated assessments, by including geographies. However, similarly to ReCiPe2016 it only covers biodiversity partly, with a focus on species diversity.
- LC-Impact was developed in 2016 and is a multi-indicator LCIA method that includes the three areas of protection (human health, ecosystem quality, resources) similar to ReCiPe2016. This method is spatialised, but like IMPACT World+ and ReCiPe2016, it focuses on species diversity and only partially covers biodiversity loss.
- The BIA+ was developed in 2018 and is a single-indicator method, developed in a PhD work and not used by other LCA practicioners, which addresses only land use. It combines habitat types with the biodiversity status and highly depends on expert judgements as database.
- BioMAPS is one of the latest developed methods (developed in 2023) and is a research project to develop a single-indicator method for reporting global operation with local downscaling for land use. Conservation and ecological datasets are used.
- GEP was developed in 2022 and delivers CFs using IUCN ecoregions, high resolution rasters and country/ ecoregion aggregates which are usable for LCIA methods.
- UNEP-GLAM (land intensity & fragmentation) is the latest developed method (2025) and a recommendation under the UNEP Life Cycle Initiative to take specific CFs in the multi-indicator LCIA method, which is usable for LCA practicioners since 2025. It is aimed to be included in SimaPro in 2026.
- The BVI was developed in 2019 and is a single-indicator biodiversity value with country level CFs focusing only on land use. It is already implemented in Sphera and new datasets are regularly published by the developers, however it is not widely used.
- PBF is a multi-indicator method developed in 2020, consisting of a selected LCIA method for three of five drivers and a semi-quantiative approach for the remaining two drivers of biodiversity loss. It is not widely used nor publicly available, nor available in any LCA tool.

Most widely used methods are ReCiPe2016, IMPACT World+, LC-IMPACT which are available in LCA Software. Recently GLAM has been used by LCA practictioners who added the method manually to the LCA software. SimaPro plans to integrate UNEP-GLAM into their software within 2026 (communication with SimaPro). BioMaps is recommended by the JRC and expected to be incorporated into the EF method by mid/end of 2026 (communication with JRC).

Table 6: Comparison of methods

Criteria	ReCiPe2016	IMPACT World+	LC-IMPACT	Product Biodiversity Footprint	Biodiversity Impact Assessment+	BioMAPS	Global Extinction Potential	UNEP-GLAM	Biodiversity Value Increment
Published in	**2016**	**2019**	**2016**	**2020**	**2018**	**2023**	**2022**	**2025**	**2019**
Category of method	Multi-indicator LCIA method (18 midpoint, 3 endpoint (AoP))	Multi-indicator LCIA method (18 midpoint, 3 endpoint (AoP) & 2 Areas of Concern)	Multi-indicator LCIA method (11 impact categories and 3 areas of protection, all on endpoint level)	Toolkit which can be fed with an LCIA method of the users choice	Single-indicator LCIA method (land use)	Single-indicator LCIA method (land use)	Single-indicator (GEPs applicable to CFs included in the ecosystem quality AoP)	Multi-indicator LCIA method (22 midpoint and 3 endpoints)	Single-indicator LCIA method (land use)
Impact categories related to biodiversity	9 mid-point categories (via damage pathways)	13 damage level indicators	7 impact cagtegories	Depends on selected LCIA method	Land use	Land use (includes some other indicators through land use intensity)	Can be applied to many impact categories	9 impact categories	Land use (includes some other indicators through land use intensity)
Overall integration of levels and drivers	**Only species diversity** 3 of 5 drivers addressed: Climate change, land use, pollution	**Only species diversity** 3 of 5 drivers addressed: Climate change, land use, pollution	**Only species diversity** 3 of 5 drivers addressed: Climate change, land use, pollution	**Only species diversity** 5 of 5 drivers addressed	**All three levels are assessed (indirectly)** 1 of 5 drivers addressed: Land use	**all three, though less focus on genetic level** 1 of 5 drivers addressed: Land use	**Explicit species extinction risk** 1 of 5 drivers addressed: Land use	**Only species diversity** 3 of 5 drivers addressed: Climate change, land use, pollution	**Emphasizes ecosystem** 1 of 5 drivers addressed: Land use
Followed LCA Framework with regard to land use indicator	UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA (Koellner et al. 2013)	builds on the general LCIA framework by UNEP-SETAC (Udo de Haes et al. 2002)	UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA (Koellner et al. 2013)	UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA (Koellner et al. 2013)	UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA (Koellner et al. 2013)	be inline with general LCA framework	Matches the requirements of the species groups covered within the GLAM methodology for ecosystem quality	UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA (Koellner et al. 2013)	UNEP-SETAC guideline on global land use impact assessment on biodiversity in LCA (Koellner et al. 2013)
Exemplary regionalisation analysis with regard to land use indicator	local / native, country and global CFs	local / native, country, continental and global CFs	local / native, country, (eco) regions, continental and global CFs	Depends on selected LCIA method	Country and (eco) region CFs	local / native, country and (eco) regions CFs	The scaling factor can be aggregated to various spatial scales. Important is to apply GEP first at the same spatial scale as the CF before aggregating to other scales	local / native, country, (eco) regions and global CFs	country and global CFs
Data gaps	Does not include ecosystem and genetic diversity	Does not include ecosystem and genetic diversity	Does not include ecosystem and genetic diversity	Does not include ecosystem and genetic diversity	Is based on expert judgements and therefore subjective	lack of inclusion of all biodiversity drivers	lacks ecosystem and genetic diversity	lacks ecosystem and genetic diversity, invertebrates not covered	

Criteria	ReCiPe2016	IMPACT World+	LC-IMPACT	Product Biodiversity Footprint	Biodiversity Impact Assessment+	BioMAPS	Global Extinction Potential	UNEP-GLAM	Biodiversity Value Increment
Exemplary data analysis with regard to land use indicator	GLOBIO3, WWF, Biodiversity Monitoring Switzerland,	GLOBIO3, WWF, Biodiversity monitoring Switzerland, various literature sources (see publication), USEtox, AWARE, GEO-Schem model,	IUCN data, species maps from other authors, WWF wildfinder database, birdlife international databases, GLOBIO, Swiss biodiversity monitoring,	The developers aim at integrating LCA databases, such as ecoinvent, agribalyse and biodiversity data such as certification schemes for biodiversity and IUCN, PREDICTS data. More specific information is not yet publicly available.	WWF wildfinder database and expert interviews.	Biodiversity Hotspot, Key Biodiversity Areas, High Biodiversity Areas, Last of the Wild, Intact Forest Landscapes, Important Bird Areas, Global 200 Ecoregions, Centers of Plant Diversity, Alliance for Zero Extinction and Evolutionarily Distinct and Globally Endangered. PREDICTS Database FAO	IUCN, ecoregions, Barbarossa et al. (2021), Borgelt et al. (2022),	PREDICTS database, HILDA+, GLOBIO4, (Mehta et al. 2022), fertilizer use (Lu & Tian), (Potapov et al. 2022), and urban area maps from the Global Human Settlement data.EltonTraits database, Verones et al.	Olson et al. 2001 Westphal & Sturm, Fehrenbach et al., Brentrup et al.. Winter et al. 2017 Ramsar Convention Secretariat Kuipers et al. 2019 Ibisch et al. 2016
Literature cited – exemplary (no complete list of reference)	de Baan et al. 2013; Elshout et al. 2014. Köllner et al. 2007, Curran et al. 2014.	de Baan et al. 2013; Chaudhary et al. 2015; Curran (2010); Thomas et al. 2004; Azevedo et al 2013 and 2015; Roy et al. 2014a,b;	Verones et al. 2013. Olson et al. 2001, Kier et al 2005. Ellis & Raankutty 2010), de baan et al. 2013. Elshout et al. 2014. Aronson et al. 2014. Chaudhary et al. 2015	Depends on selected LCIA method	Lindner et al. (2014), Kiellner et al. (2013) and is based on Michelsen (2008)	Hurtt et al. 2011; Newbold et al. 2015&2016; Hudson et al. 2014; Jenkins et al. 2013;	Kuipers et al. 2019; Montesino Pouzols et al. 2014;	Gallego-Zamorano et al. 2022, Chaudhary et al. 2015	Lindner work, Winter et al. 2017, Maier et al.
Overall applicability & usage in tools like Simapro / sphera	Yes, this method is widely accepted and used in LCA software	Yes, integrated into LCA software	This method can be used in LCA software tools. Widely accessible for LCA practicioners	This method is not publicly available and therefore cannot be used by the community	Not widely used	Not widely used,possibly integration with LANCA land use model	Implementable via CFs, but not a "bundle" method in all tools	It is aimed to be included in LCA software tools starting from 2026 onwards as the method in its formatting is compatible with the tools	CFs are available in LCA Software packages for OpenLCA 2.1.0 and Sphera LCA For Experts. Conversion plugins for OpenLCA exist which facilitate the integration of data into SimaPro
Reference list of usage	Papers using this method are available	Papers using this method are available	Case studies within the funded project	Very few case studies by the authors	One case study within the phd thesis	One case study within the phd thesis	Used in some case studies	Very recent papers using this method are available	The authors did some case studies
Unit of biodiversity loss	species * year	PDF*m²*year	PDFglobal * year	Depends on selected LCIA method for 3 of five drivers, no unit for other two drivers.		PBR*m²*year	GEP (Global Extinction probability, dimensionless)	PDF * year	BVI (global biodiversity value)

6 Current challenges to include biodiversity in LCA generally

Currently, there are many challenges to include biodiversity in LCA. One of the main challenges is the lack of data availability in various areas, although data availability has increased throughout the last 10 years, as evident by the regionalization in various LCIA methods and advances in including GIS information in LCA. Areas which are lacking in data availability include, among others, coverage of all levels of biodiversity (genetic, species and ecosystems), management practices and impact pathways. Additional challenges are identified in the complexity of biodiversity, applicability, implementation and compatibility of methods, among others. In this chapter the following challenges are briefly discussed:

1. Genetic biodiversity
2. Ecosystem and species diversity,
3. Impact pathways,
4. Various spatial scales,
5. Management practices in agriculture
6. Indicator selection – PDF vs. MSA
7. Applicability, implementation, compatability
8. Implementation in LCIA method and LCA software
9. Complexity of biodiversity

1. Genetic biodiversity (variability) is hardly considered in the LCA biodiversity methods. It can be reasonably assumed that genetic variability is larger than species diversity, for which data availability is a challenge considering the large majority of species on earth are undescribed. Nonetheless, genetic variability is important in the context of biodiversity as it is related to adaptability and to prevent inbreeding. Reductions in genetic variability, through for example habitat fragmentation, can result in biodiversity losses.

2. Similar, there are still data gaps to address species and ecosystem biodiversity, even though it is being included in some methods. In general, data availability for aquatic diversity is lower compared to terrestrial (Siqueira et al. 2014). The data used to quantify the impact on biodiversity in LCA often rely on species diversity data. The GEP covers data for around 100 000 species, the IUCN red list has assessed roughly 170 000 species, estimating that 2.1 million species have been described, while a commonly cited figure for the total number of species on earth is 8.7 million (Mora et al. 2011). These numbers alone present evidence of the lack of data, even regarding species diversity. Moreover, the type of species covered is disproportionally distributed. The GEP covers a large fraction of mammals and birds, however invertebrates, plants, fungi and algae are underrepresented. Species coverage in the GEP is higher compared to other methods.

3. **Another main challenge is that impact pathways are not, yet, fully understood and addressed for many pressures.** For various pressures lack of data is a problem (for example odour or noise), for others the modelling of the impact pathways is lacking. For example cause-effect relationships between (local) land use management practices and biodiversity are challenging, or the effect of habitat fragmentation. Other data gaps include the lack of toxicological data on all substances, as well as uncertainty associated with (toxicological) data and impact pathway models. Nonetheless this should not mean to focus on one better known pressure only. It rather shows that there is more development necessary and that quantifying biodiversity pressures is complex from various perspectives.
4. Moreover, the effects on various spatial scales make interpretion more difficult. A loss of biodiversity on the local level may not have global consequences, when the species in question remains abundant in other regions. Therefore local impacts may be different from global impacts. This can present challenges in LCA, as the inventory may have different spatial resolutions; sometimes only country of origin is known whereas in other situations the exact production location is known. Therefore any method to quantify biodiversity requires easy use at various spatial levels as well as the possibility to use either specific or generic data.
5. Recently, some methods, notably BioMAPS and the UNEP-GLAM, started to include land use intensity parameters. Land use intensities could be used to more accurately describe the land use impacts. Coelho et al. (2025) apply the UNEP-GLAM method to assess the impacts of cropland on biodiversity, highlighting two interesting aspects; firstly, they only assess land use-impacts and note that "other impact categories, such as ecotoxicity, may be of interest when assessing agricultural systems, their concomitant use could result in double-counting" (Coelho et al. 2025). Secondly, they argue CFs should be updated to avoid misleading interpretations, as, from a product perspective, higher yields require less land thereby reducing impacts on biodiversity, however higher yields generally require intensification which has a negative impact on biodiversity. A meta-analysis shows that small step conventional intensification can increase yields without biodiversity loss, but overall, intensification boosts yield (+20,3%) but reduces species richness (-8,9%) (Coelho et al. 2025 referring to Beckmann et al. 2019). Small step conventional intensification requires mechanisms such as zoning, supply chain governance and enforcement coupled with economic incentives, to be effective (Börner et al. 2014, Gibbs et al. 2015, Phalan et al. 2016).
6. Most methods considered in this study use PDF to quantify the impact on ecosystems. Recently, some LCAs have been published using the loss of MSA (Mean Species Abundance) as to quantify impact on biodiversity, for example de Weert et al. (2025). The MSA indicator estimates the average abundance, richness, and geographical extent of species relative to the expectation in a pristine site that serves as a reference (Alkemade et al. 2009), whereas PDF is an indicator for potential long-term species extinction (Damiani et al. 2023). Loss of species abundance occurs before species loss and thus MSA may serve as an early indicator for biodiversity loss. **The use of different methods as well as units in which biodiversity impacts are expressed presents additional challenges in terms of comparability of the results.** In a recent publication by Kuipers et al. (2025) the correlation between MSA and PDF has been investigated to evaluate the extend of the indicators providing complementary or redundant information. In their work, they show that there is a consistent positive relationship between loss of MSA and PDF, while simulatniously highlighting that MSA is more sensitive and the spread of MSA is higher especially when PDF values are low (Kuipers et al. 2025). MSA and PDF assess different aspects of biodiversity, with PDF considering only the presence or absence of species, whereas losses in abundance, captured in MSA, may be more relevant from an ecosystem functioning

perspective. Furthermore, various authors point out that MSA is likely more affected by demographic and environmtenal stochasticity (random variations in life events, such as births and deaths, and environment) and abundance compensation (loss of individuals of one species may be compensated by the increase of individuals in another), thus local contexts and environments may also play a role (Santini et al 2017, Valdez et al. 2023, Blowes et al. 2022). As also shown in this study, the use of MSA in LCA is not established yet, although first approaches are being developed, therefore characterization factors for PDF are further developed compared to MSA. Kuipers et al. (2025) conclude that MSA loss and PDF provide different and complementary informations.

MSA has been developed in the framework of GLOBIO3, which focusses on the assessment of simple cause-effect relationships between environmental drivers and biodiversity impacts. Drivers included are land-coverage change, land use intensity, fragmentation, climate change, atmospheric nitrogen deposition and infrastructure development. The framework focusses enabling the evaluation of expected trends under various future scenarios and effects of policy response options, thus developed specifically with policies in mind. It may face some challenges related to product related assessments, as in LCA, methodological choices are made different when assessing policies and products. Fundamentally, there is a difference in goal and scope set out by policy and product related LCAs and impact assessments. It must be highlighted that GLOBIO is used as source of data by various LCIA methods to cover impacts on biodiversity or ecosystem quality. Furthermore, there are challenges related with using MSA such as data collection, the use of reference states, interpretation due to the complexity of the calculation and pressures covered. However, the further development of complementary approaches such as MSA can provide additional insights in the many dimensions of biodiversity, enabling the use of more comprehensive assessment of impacts and guide efficient decision making. Moreover, it should be considered if a single indicator can adequately cover biodiversity, given the complexity of biodiversity, as well as the application of LCA to answer a wide variety of research questions.

7. The development of various approaches, as currently seen in science and also recommended above, comes with a set of challenges related to applicability, implementation, compatability and potential risks of double counting. Firstly, due to the large ongoing effort of the scientific community in the development of methods, comprehensive documentation is important for various reasons. It enables better and easier implementation and improves the overall applicability and it allows the LCA community to better understand the approaches, their suitability and interpretation. Secondly, the implementability of impact assessment methods depends on the selection of impact pathway models. For example, for the UNEP GLAM method and the Environmental Footpint (EF) methodology recommended by the JRC, there exist different underlying acidification and terrestrial eutrophication models for their impact assessment models. In the EF, the BioMAPS-model will be recommended for implementation through the development of a new indicator "Land use – biodiversity" at mid-point level, with the currently present land use indicator being renamed to "Land use – Soil Quality Index". In a telephone call with the PEF developers in September 2025, it was stated that there is currently no intention to model impact pathways beyond mid-point indicators for the EF (personal communication). The implementation of impact pathway models in LCIA methods depend on the selection and compatibility of the mid-point

impact pathway models. Methods such as ReCiPe and the UNEP GLAM method aggregate various impacts into endpoint indicator "ecosystem quality", in order to compare different impact categories (Woods et al. 2018). To achieve this, indicators at damage level need to be comparable and are usually aggregated from impacts, which may be partially derived from similar underlying datasets relating impacts to species loss. A consequence of longer impact pathway models is increased uncertainty and it may include the risk of double counting. Ecosystems quality is a multifaceted area of protection, of which biodiversity is key aspect, but can encompass more (such as ecosystem services). As such, there are additional elements which are yet to be considered and go beyond biodiversity and vice versa. As highlighted in this study, the units of the AoP ecosystem quality tend to be PDF, which serves as a proxy for biodiversity, making the terminology used somewhat confusing and adding to the uncertainty.

8. The implementation of methodologies in databases and softwares takes time, and may require updating life cycle inventories in the databases to include more specific elementary flows (for example related to land use and land use change flows, or regionalisation). Over the last decade, many developments within the assessment of biodiversity in LCA have been made and various methods have been implemented in LCA software. Before a method is integrated, it is thoroughly tested. If necessary, life cycle inventories are extended and the new method and datasets are implemented in LCA software and databases, however native resolution characterization factors are generally aggregated before inclusion in software. Nonetheless, native scale resolution may be useful in modelling foreground systems, given that spatially explicit data for background processes is generally difficult to obtain. This represents a trade-off between data requirements, time, computational effort on the one hand and accuracy, depth and precision on the otherhand. The implementation of novel methodologies in software takes time, which can be illustrated by the time between the publication of the BioMAPS methodology (2022) and its potential implementation in the EF (expected by JRC in 2026). This excludes the time it took to develop BioMAPS as well as the underlying methods and models. Since biodiversity is a complex system which changes over time, characterization factors used in LCA software may need to be updated regularly. Moreover, methodological updates may be made or new aspects may be added to existing methods. Therefore, the implementation of the methodologies in databases and software is a challenge to making them available and operatable. Coordinated efforts (closer cooperation between e.g. scientists and JRC and software developers) can mitigate this challenge to a certain extend.

9. The authors would like to acknowledge the high complexity of biodiversity. Not only are ecosystems highly complex and not fully understood by science, an additional main challenge is relating these complex systems to the life cycle of a product. Due to the complexity of ecosystems, the systems are non-linear which means that two combined pressures may result in a different impact compared to the sum of the two individual pressures. This makes it challenging to quantify the impact of a product specifically. Furthermore, in product LCAs, activities not related to the product system are considered outside of the system boundaries, however the aggregated activities in an area impact (local) biodiversity. This means that activities traditionally considered outside the system boundaries can influence the magnitude of biodiversity impacts which makes it challenging to link isolated activities to biodiversity loss. The location of impact also plays a role and adds complexity. In IMPACT World+ it is shown, that the range of impact of an emission is larger than the difference between the substances (Bulle et al. 2019). This indicates that the location of the emission may be more important than the substance emitted. For LCA practitioners, all these aspects increase the complexity of the interpretation of the results.

In addition to the challenges above, it must be highlighted that depending on the goal, scope and research question, the suitability of LCA to quantify biodiversity impacts should be evaluated. LCA can be used for a wide variety of goals which include for example

- understanding and mitigating biodiversity impacts of products and value chains,
- decision making during product and process development,
- to inform consumers and the general public,
- monitoring impacts over time and to assess policies or entire sectors.

In LCA, the goal and scope definition influences methodological choices. It can be considered one of the strengths and weaknesses of the general LCA methodology at the same time (ISO 14040 & ISO 14044). The strength lies in the methodological flexibility to answer a wide variety of questions, whereas that same flexibility results in complexity in the interpretation, which can make the comparison of different LCAs challenging. With regard to biodiversity in LCA, this means that, at the moment, the tool is challenging to use for some goals, such as informing consumers or society, or mitigating biodiversity impacts of product value chains. For high level biodiversity risk screening and understanding biodiversity impacts of product value chains, LCA approaches can be applied as part of a broader methodological toolkit (not exclusively LCA) to provide more robust answers to the specific research questions. For such applications, it is recommended to use the UNEP GLAM method or the BioMAPS method, preferably both, as biodiversity method in LCA. Nonetheless, due to the complexity and uncertainty of biodiversity assessments, generally more time and effort is required to provide meaningful answers, compared to a LCA which does not consider biodiversity.

Currently, the most reliable way to mitigate local biodiversity loss risks or promote local biodiversity is through certification which includes scientifically proven measures beneficial for biodiversity. Several regulations have included biodiversity related aspects to mitigate the risk of biodiversity loss, for example the REDIII through the implementation of criteria for the sustainable sourcing of biomass, which includes provisions to protect high-biodiversity value areas. Several certification schemes include provisions related to high biodiversity value area conservation and/or aim to restrict land use changes.

7 Summary, conclusion and recommendation

Biodiversity and the influence of companies and products on biodiversity loss is an emerging topic of interest. Within the RCI, the question of biodiversity loss due to agricultural activity arose. This report is the second of three interconnected parts and has the goal to transparently show the efforts with regards to biodiversity assessment for a terrestrial environment in Life Cycle Assessment (LCA), and subsequently discuss applicability as well as open research questions. Part one summarises current knowledge of causes and consequences of biodiversity decline, global and European policies in support of bioeconomy and/or biodiversity, and the trade-off between biomass production and biodiversity conservation. And part three lists agricultural and forestry-related measures that individually or in combination can protect, or even increase biodiversity without compromising the biomass production, and discusses best-practises on the basis of global case studies.

According to the offer to RCI, following methods from the last ten years are analysed through a literature review:

- ReCiPe2016 (Huijbregts et al., 2017),
- IMPACT World+ (Bulle et al., 2019),
- LC-IMPACT (Verones et al., 2020),
- Product Biodiversity Footprint (Asselin et al., 2019)
- Biodiversity Impact Assessment+ (Winter et al., 2018)
- BioMAPS (Maier, 2023) & possible Biodiversity Loss Potential within the LANCA method & relation to PEF
- Global Extiction Potential (Verones et al., 2022)
- UNEP-GLAM (2025)
- Biodiversity Value Increment (Lindner et al., 2019)

The methods are evaluated with regard to

- Overall integration of biodiversity levels and drivers
- Exemplary data analysis
- Exemplary regionalisation analysis
- Overall applicability & usage – e.g., usage in software tools like Simapro / sphere & list of reference, where the method already has been applied.
- General aspects

The development of LCA specific characterization factors are exemplarily explained with a focus on land use, as the indicator land use is described in each investigated method and this can be used to compare the different methods. The other impact categories are visualized and compared in the comparison chapter.

The result of this study is that none of the investigated approaches fully and simultaneously address all three levels of biodiversity (ecosystem, genetic and species level) and all five drivers (climate change, habitat loss, pollution, overexploitation, invasive species) within one LCIA method. The selected methods can be distinguished being a multi- or a single-indicator method. A single-indicator method is not likely to include all five drivers, whereas a multi-indicator is more likely to include more drivers. The single-indicator methods BIA+, BVI and BioMAPS are dedicated methods to assess biodiversity via the indicator land use. GEP is a method that can be applied to a selected single-indicator. The multi-indicator methods (ReCiPe2016, LC-IMPACT, IMPACT World+, GEP, UNEP-GLAM) include the biodiversity loss drivers land use, climate change and pollution. They also include additional pressures like water use, GHG, toxic, acidifying, nutrient and other air emissions, relevant for biodiversity assessment, and emissions in water and soil that mostly are included in characterisation factors. Invasive species, overexploitation, genetic or ecosystem level are usually not covered. The Product Biodiversity Footprint method aims to assess all five drivers, however, similar to most other methods, focuses on species diversity only. In PBF land use, climate change and pollution are addressed with an LCIA method and the other two drivers overexploitation and invasive species are addressed in a semi-quantiative way.

Publicly usable are ReCiPe, LC-IMPACT, IMPACT World+ and UNEP-GLAM recommendations. The first three methods are already available in LCA software. Recently GLAM has been used by LCA practictioners who added the method manually to the LCA software. SimaPro plans to integrate UNEP-GLAM into their software within 2026 (communication with SimaPro). BVI is less widespread. BIA+ is a research project which does not have specific further use cases. PBF is neither publicly available nor available as a paid service. The GEP has been included in the UNEP-GLAM recommendations. BioMAPS has been developed in a research project and is proposed to be incorporated as "land use – biodiversity" indicator in the next version of PEF (JRC), which is expected by JRC to be released by mid/end of 2026 (personal communication with JRC in September 2025). However, there is still a discussion ongoing and timeframes might change.

The last decade has seen great progress in the development of methods and data for the inclusion of biodiversity in LCAs. However, there are still significant challenges on the road ahead. This includes challenges related to data availability and quality, impact pathway modelling, uncertainty, how and what to cover whith which method, interpretation and implementation. Given the rate at which the development takes place, it is recommended to regularly check for updates in LCIA methods, models and data, to be aware of the latest developments. Furthermore, during the use of LCA to assess impacts on biodiversity, **it is recommended to acknowledge the uncertainty in the current models and methods**. Additionally, the approach to assess biodiversity impacts depends on the goal, scope and research question of the assessment.

The methods were developed within the last ten years and either build on each other, incorporate some aspects of each other or use the same/similar data sources. GLAM and BioMaps are the most recent methods and include methodological aswell as data aspects/sources from former methods. BioMaps focuses on land use aspects only, as the authors want to assess biodiversity loss from a land use perspective in a single-indicator method. GLAM as a multi-indicator method takes various aspects into account to assess biodiversity loss. GLAM uses data from GLOBIO4, the latest update of GLOBIO. Both methods use data from PREDICTS database and others, which are in common with former methods. Additionally, the JRC has identified BioMaps as a good basis for land use biodiversity assessment to be incorporated into the EF method. This is an advantage for this method. Therefore, **for high level risk biodiversity screening, e.g. for companies, the authors of this study recommend using the UNEP-GLAM method and BioMAPS within the EF methodology (once available), along with the use of a broader methodological toolkit (like certification schemes and field measurements) to assess biodiversity impacts to provide a more robust answer to the specific research question.** Similar to other choices in LCA, also with regard to biodiversity assessment, the choice of method directly influences the hotspot identification and therefore strategy and resource allocation. **To avoid biased choices, sensitivity analysis by using different methods and adding other biodiversity evaluations are recommended. Current methods can be applied to generate an understanding of biodiversity impacts of product value chains, but should be confirmed with additional assessments.** It is not recommended to inform consumers using LCA approaches, due to a multitude of challenges based on the current state of biodiversity assessments in LCA. For the development of mitigation strategies, it is recommended to use scientifically proven measures stimulating biodiversity on site or throughout the value chain. A broader application of biodiversity assessment methods in LCA, through for example case studies, improves the understanding of the methods and allows refinement of the methods as well as validation of the LCA methodologies with other biodiversity assessment approaches and methods.

Finally, **it is highly recommended to further develop biodiversity assessment methods in LCA as the last decade has shown great progress.** Biodiversity loss is caused by a lot of pressures. Focusing on a single indicator to tackle biodiversity loss therefore would seem not adequate and focusing on including several drivers of biodiversity loss into the assessment would seem more adequate (If double-counting of pressures with other indicators is avoided). However, as the developments are on going and so far no scientific consensus has been arranged, it is more important to tackle the quantification of biodiversity loss in a way that is possible, instead of not doing it at all. The JRC is planning on looking out for other developments to being able to include more drivers in the future (personel communication). For the time being, they think that taking the BioMaps as land use model for biodiversity loss is correct. Further development of land use intensity parameters in biodiversity assessment, as well as in LCA in general, is recommended. The further development should focus on combining the expertise of biologists, conservationists, ecologists and LCA and modelling experts, to deepen our understanding of ecosystems and advance the inclusion of biodiversity assessment in LCA. The interdisciplinary approach is important to cover all relevant aspects and presents a opportunity for policy makers to support the development through providing funding for the research and implementation. Data gaps exist with regard to inclusion of all taxonomic groups, integrating all biodiversity pressures, drivers and levels in one methodology. All of the methods therefore do not cover full biodiversity and are proxies. The future development of all these methods should focus on integrating all of pressures and groups. This implies a lot of work of biologists around the world to measure biodiversity loss per piece of land and also by other scientists to build up cause-effect chain models to create specific characterization factors, which can be used in LCA. To enhance exchange and widen applicability, clear documentation is of the approaches is recommended, which is also practical in the interpretation and evaluation of case studies and verification of results. Challenges in the interpretation of LCAs including biodiversity will become more relevant when the application increases, therefore the use of various indicators should be considered.

However, during the further methodological development of biodiversity assessment using LCA, including the implementation in databases and LCA software, it can be also effective to focus directly on reducing known pressures on biodiversity (LCA midpoint categories, like climate change).

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Personal communication: the authors from nova Institute (Mika Plum and Niels de Beus) had a video call with staff from JRC (Laura Garcia-Herrero, Esther Sanye-Mengual, Giulia Listorti) on the 25 September 2025 to talk about their latest biodiversity assessment developments.

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8 Annex

The sections listed in this appendix were originally included in the section on methodology. In order to reduce complexity and focus on the most important points in the main body of this report, this information has been placed here instead of removing it. This way, the reader can read these parts optionally.

8.1 ReCiPe2016 – Calculation of ecosystem quality CFe, exemplarily from land use CFm

According to ReCiPe2016 and the authors of the land use chapter P.M.F. Elshout, Z. J. N. Steinmann and M. A.J. Huijbregts, land use focuses on the relative species loss due to local land use. The cause-effect chain of land use and its' effects on ecosystem quality is visualized in Figure 8. If a certain terrain is used in a specific way, the land cover changes and or the way how the land is used gets intensified. This intensification leads to soil disturbance. A change of land cover and land use intensification lead to loss of habitat. Either loss of habitat or soil disturbance lead to loss of species, defined as potentially disappeared fraction of species which finally leads to damage of the ecosystem.

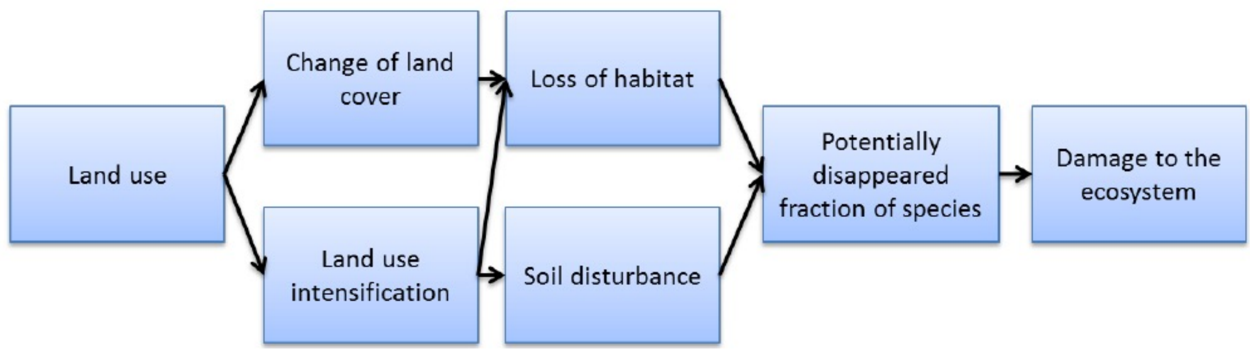

Figure 9: Cause-and effect chain of land use, leading to relative species loss in terrestrial ecosystems. Relative species loss due to land-use induced climate change are excluded from this impact category and included in the climate change category (ReCiPe2016)

Local land use includes three steps, see Figure 9:

1. First, the land is transformed to its new function (Transformation),
2. then, it is occupied (Occupation) and
3. finally it is released to the environment again, in which it may relax to a state, similar or equal to its untransformed state. (Relaxation)

Data on the type of used land and the time period in which it is used, is needed to calculate the the characterization factors. The steps transformation and occupation are covered in the CFs for land occupation (CFocc) and have the unit Potentially Disappeared Fraction of Species (PDF) per annual crop equivalent. Those

CFs are based on relative species losses calculated by De Baan et al. (2013) and Elshout et al. (2014). For the relaxation step, it is assumed that some negative effects on species richness are still in place over time until the land had the possibility to recover. When the land is no longer used, recovery begins (realaxation) and the land can return to a (semi) natural state. During this phase, the land still has some negative effects on biodiversity, as recovery takes some time and it will most likely not return to its original habitat, but to a different state. CFs for land relaxation are expressed in PDF * year per annual crop equivalent and based on the model from Köllner et al. (2007) with recovery times from Curran et al. (2014). The reference situation is based on a natural situation in which no land use has taken place. For the comparison, the relative species richness is assessed. (ReCiPe2016)

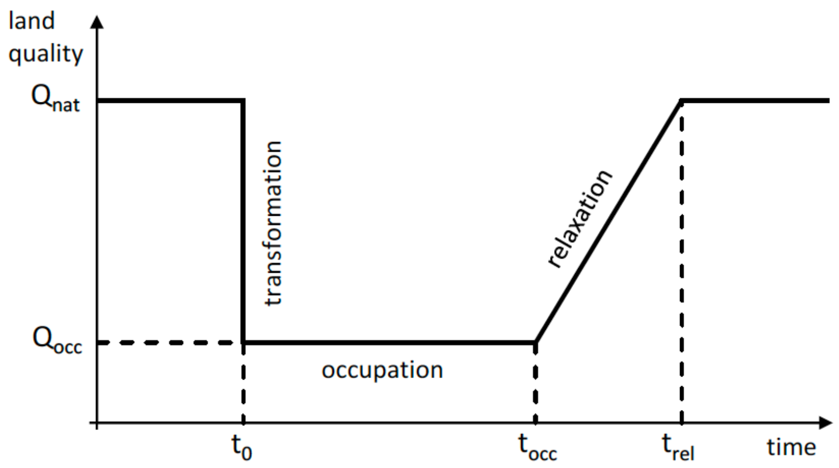

Figure 10: Schematic overview of land transformation (at t0), land occupation (t0 – tocc) and land relaxation (tocc – trel) and their impact on land quality (ReCiPe2016)

Calculation of midpoint characterization factors for land use

The midpoint characterization factors in annual crop equivalents for land transformation / occupation CFm_{occ} is based on the relative species loss S_{rel} for land use type x, divided by the relative species loss from annual crop production:

$$CFm_{occ,x} = \frac{Srel_x}{Srel, annualcrop}$$

Whereof, S_{rel} is cacluated by comparing field data on local species richness in specific types of natural and human-made land covers with the linear relationship from Köllner et al. (2007). and are observed species richness per land use type x, ref for reference land cover, in region i.

$$Srel_x = 1 - \frac{S_{LU,x,i}}{S_{ref,i}}$$

The total world averages of relative species losses (Srel) due to land transformation / occupation by De Baan et al. 2013 are shown in Table 7.

Table 7: Total world averages of relative species losses (Srel) due to land transformation / occupation by De Baan et al. 2013 from ReCiPe2016.

Land use type	S_{rel}
Pasture and meadow	0.33
Annual crops	0.60
Permanent crops	0.42
Mosaic agriculture	0.2
Artificial areas	0.44

The midpoint characterization factors in annual crop equivalents * year for land relaxation CFm_{relax} is calculated as follows:

$$CFm_{relax,x} = CFm_{occ,x} * 0.5 * t_{rel}$$

According to Curran et al. 2014, the duration of relaxation (trel) can vary depending on passive or active recovery. Whereas passive recovery describes a natural occurring recovery of the selected are, active recovery describes a process, in which humankind actively restores the habitat by replacement of soil, reforestation and animal reintroduction. The recovery of species richness can be accelerated by 80%, which is reflected in the CF. The typical trel for passive recovery is calculated in Curran et al. 2014 to be 33.9 years. (ReCiPe2016)

The species richness in different types of natural vegetation can vary considerably, which is why different CFs are specified for different types of land use and different species, see Table 9 and Table 8. The effects of land conversion from one anthropogenic land use to another are not addressed in ReCiPe2016.

Table 8: ReCiPe2016 midpoint CFs for CFmocc (based on data from De Baan et al. 2013) and CFmrelax on specific species groups. The recovery times are collected from Curran et al. 2014)

	CFm_{occ} (annual crop eq)				**t_{rel} (year)**											
					mammals		*birds*		*insects*		*invertebrates*		*plants*		*trees*	
Land use type	*mammals*	*birds*	*arthropods*	*vascular plants*	*forest*	*open*	*forest*	*Open*	*forest*	*open*	*forest*	*open*	*forest*	*open*	*forest*	*open*
Pasture and meadow	0.55	0.33	0.42	0.18	69.4	7.2	68.6	6.3	69.2	7.0	79.5	8.0	73.5	7.3	102.2	10.4
Annual crops	0.75	0.88	1.08	0.70	69.4	7.2	68.6	6.3	69.2	7.0	79.5	8.0	73.5	7.3	102.2	10.4
Permanent crops	0.45	1.03	0.93	0.47	69.4	7.2	68.6	6.3	69.2	7.0	79.5	8.0	73.5	7.3	102.2	10.4
Mosaic agriculture	-0.23	0.37	0.07	0.62	69.4	7.2	68.6	6.3	69.2	7.0	79.5	8.0	73.5	7.3	102.2	10.4
Artificial areas	-	-	-	-0.70	69.4	7.2	68.6	6.3	69.2	7.0	79.5	8.0	73.5	7.3	102.2	10.4

	CFm_{relax} (annual crop eq·yr)											
	mammals		*birds*		*insects*		*invertebrates*		*plants*		*trees*	
Land use type	*forest*	*open*	*forest*	*open*	*forest*	*open*	*forest*	*open*	*forest*	*open*	*forest*	*open*
Pasture and meadow	19.1	2.0	11.4	1.1	14.4	1.5	16.6	1.7	6.7	0.7	9.4	1.0
Annual crops	26.0	2.7	30.3	2.8	37.5	3.8	43.1	4.3	25.7	2.5	35.8	3.6
Permanent crops	15.6	1.6	35.5	3.3	32.3	3.3	37.1	3.7	17.2	1.7	23.8	2.4
Mosaic agriculture	-8.1	-0.8	12.6	1.2	2.3	0.2	2.7	0.3	22.7	2.2	31.5	3.2
Artificial areas	-	-	-	-	-	-	-	-	-25.7	2.5	-35.8	-3.6

Table 9: Midpoint CFs for the impact of land transformation / occupation (CFm_{occ}) and land relaxation (CFm_{relax}) on total species richness according to ReCiPe2016.

Land use type	CFm_{occ} (annual crop eq)	CFm_{relax} (annual crop eq·yr)
Used forest	0.30	5.1
Pasture and meadow	0.55	9.3
Annual crops	1.00	17.0
Permanent crops	0.70	11.9
Mosaic agriculture	0.33	5.6
Artificial areas[1]	0.73	12.4

[1]urban areas, industrial areas, road and rail networks, dump sites.

Table 10: ReCiPe2016: Exemplary data set description (ecoinvent) and ReCiPe2016 CFm definition for those data sets

Name	Midpoint CF (annual crop equivalents·yr)
Transformation, from grassland, natural (non-use)	3.75
Transformation, from forest, primary (non-use)	36.75
Transformation, from forest, secondary (non-use)	36.75
Transformation, from shrub land, sclerophyllous	3.75
Transformation, from wetland, inland (non-use)	3.75
Transformation, to shrub land, sclerophyllous	-3.75
Transformation, to forest, secondary (non-use)	-36.75
Transformation, to wetland, inland (non-use)	-3.75
Transformation, to grassland, natural (non-use)	-3.75

Name in Ecoinvent	Name in ReCiPe
Occupation, pasture, man-made, intensive	pasture
Occupation, permanent crop, non-irrigated, intensive	permanent crops
Occupation, mineral extraction site	artificial area
Occupation, annual crop, greenhouse	artificial area
Occupation, permanent crop, irrigated, intensive	permanent crops
Occupation, industrial area	artificial area
Occupation, construction site	artificial area
Occupation, annual crop, non-irrigated, intensive	annual crops
Occupation, traffic area, road network	artificial area
Occupation, annual crop, irrigated, intensive	annual crops
Occupation, dump site	artificial area
Occupation, river, artificial	-
Occupation, annual crop	annual crops
Occupation, lake, artificial	-
Occupation, annual crop, non-irrigated, extensive	annual crops
Occupation, traffic area, rail/road embankment	artificial area
Occupation, pasture, man-made, extensive	pasture
Occupation, forest, extensive	managed forest
Occupation, forest, intensive	managed forest
Occupation, permanent crop	permanent crops
Occupation, traffic area, rail network	artificial area
Occupation, seabed, infrastructure	-
Occupation, seabed, drilling and mining	-
Occupation, annual crop, non-irrigated	annual crops
Occupation, shrub land, sclerophyllous	managed forest
Occupation, annual crop, irrigated	annual crops
Occupation, urban, discontinuously built	artificial area
Occupation, pasture, man-made	pasture
Occupation, grassland, natural (non-use)	-
Occupation, urban/industrial fallow (non-use)	artificial area

Calculation of endpoint CFs for ecosystem quality from land use midpoint CFs

The calculation of ecosystem quality is done with the help of midpoint CFs. On the cause-effect chain, after the midpoint level, all environmental mechanisms are considered to be identical for each impact category. Therefore, for each ecosystem quality influencing midpoint impact category, an endpoint characterization factor is formulated by multiplying the midpoint CF with a defined factor. Therefore, the endpoint characterisation factors (CFe) are derived from midpoint characterisation factors (CFm) per land type x multiplied with a factor per impact category (). Consequently, endpoint results have a higher uncertainty than midpoint results.

$$CFe_x = CFm_x * F_{m\to e} \quad \text{so} \quad CFe_{occ,x} = CFm_{occ,x} * F_{m\to e} \quad \text{and} \quad CFe_{relax,x} = CFm_{relax,x} * F_{m\to e}$$

The midpoint to endpoint factors are constant per impact category. For terrestrial ecosystems, the midpoint to endpoint factor is calculated with:

$$F_{m\to e} = SD * Srel, annual\ crops$$

- SD = 1.48·10-8 species.m-2 and is the average approximated species density for terrestrial ecosystems according to (Goedkoop et al., 2008). (ReCiPe2016)
- Srel,annualcrops = 0.6 (De Baan et al. 2013)

The endpoint CFs for land occupation / transformation and relaxation are displayed in Table 11.

Table 11: ReCiPe2016 endpoint CFs for land occupation (CFeocc) and land relaxation (CFerelax) on total species richness

Land use type	**CFe_{occ} species·/m²**	**CFe_{relax} species·yr/m²**
Used forest	2.66E-09	4.52E-08
Pasture and meadow	4.88E-09	1.51E-07
Annual crops	8.88E-09	8.28E-08
Permanent crops	6.22E-09	1.05E-07
Mosaic agriculture	2.93E-09	4.97E-08
Artificial areas	6.48E-09	1.10E-07

The global midpoint to endpoint factor for land use for terrestrial ecosystem quality is reported in Table 12. (ReCiPe 2016)

Table 12: ReCiPe 2016 land use constants for midpoint to endpoint characterisation factors of the standard (hierarchist) characterisation factors for terrestrial ecosystem quality

	Unit	
Ecosystem quality: terrestial		
Land use	species/m² annual crop land	8.9E-09

8.2 IMPACT World+

The table below is taken from the methodological publication and shows the midpoint level impact category, damage level impact category, the associated area of protection and concern, recommendation on the inclusion in the methodology, references, native geographical scale of the indicator, time resolution, information on aggregation approaches as well as the number of elementary flows covered in the indicators.

Table 13: Overview of the midpoint- and damage level impact categories, taken from Bulle et al., 2019

- (dark grey) Shorter term impact (occuring between 0 and 100 yrs after the environmental intervention occur)
- (light grey) Long term impact (occuring 100 yrs after the environmental intervention)
- (hatched) Timely resolved impact with both shorter term (0-100 yrs) and long term impacts (more than 100 yrs)

Midpoint level impact category (*proxy midpoint)	Damage level impact category	Area of protection (AoP)	Area of concern (AoC)	Recommended (R) or *Interim (I)*	References	Native geographical resolution scale	Time resolution	Emission/consumption data or proxy used to agregate CFs at country level, continental and global scales	Number of elementary flows
Climate change, long term*				**R**	Levasseur et al. 2016; de Schryver et al. 2009; Joos et al. 2013; Myhre et al 2013;	Global			212
Climate change, short term*				**R**					
	Climate change, human health	**HH**	**Carbon, HH**	**R**					
	Climate change, ecosystem quality	**EQ**	**Carbon, EQ**	**R**					
	Climate change, ecosystem services	*R&ES*		*I*					
	Marine acidification	**EQ**	**Water, EQ**	**R**	Myhre et al 2013; Azevedo et al. 2015	Global			9
Ozone layer depletion	**Ozone layer depletion**	**HH**	**Rest of HH**	**R**	Margni et al. 2008; Struijs et al. 2009	Global			23
Mineral resources use	*Mineral resources use*	*R&ES*		**R at midpoint** *I at damage*	de Bruille 2014	Global			165
Fossil energy use	*Fossil energy use*	*R&ES*		**R at midpoint** *I at damage*	Fatemi 2012; Frischknecht 2003	Global			37
Terrestrial acidification	**Terrestrial acidification**	**EQ**	**Rest of EQ**	**R**	Roy et al. 2014a; Roy et al. 2012a; Roy et al. 2012b	2° x 2.5°		Acidifying subtances emissions in each 2°x2.5° cell intersection the country/ continent / globe	15
Freshwater acidification	**Freshwater acidification**	**EQ**	**Water,EQ**	**R**	Roy et al. 2012b; Roy et al. 2014b	2° x 2.5°			15
Marine eutrophication	**Marine eutrophication**	**EQ**	**Water, EQ**	**R**	Roy et al. 2012b;	2° x 2.5°		Atmospheric emissions of N containing subtances in each 2°x2.5° cell intersectiing the country/ continent / globe	16
Freshwater eutrophication	**Freshwater eutrophication**	**EQ**	**Water,EQ**	**R**	Helmes et al. 2012; Tirado-Seco 2005	0.5° x 0.5°		Population density used as a proxy of P emissions in each 0.5°x0.5° cell intersectiing the country/ continent / globe	8
Freshwater ecotoxicity	**Freshwater ecotoxicity**	**EQ**	**Water, EQ**	**R**	Hauschild et al. 2008; Rosenbaum et al. 2008; Kounina et al. 2014; Huijbregts et al. 2005; Hellweg et al. 2009; Rosenbaum et al. 2015; Wenger et al. 2012; Fantke et al. 2011; Fantke and Jolliet 2016; Fantke et al. 2012	Continent		USEtox default version used for global default CFs	2516
	Terrestrial ecotoxicity	*EQ*		*I*					
	Marine ecotoxicity	*EQ*		*I*					
Human toxicity cancer	**Human toxicity cancer**	**HH**	**Water, HH Rest of HH**	**R**		Continent + high/low population and indoor archetypes			1020
Human toxicity non-cancer	**Human toxicity non-cancer**	**HH**	**Water, HH Rest of HH**	**R**					439
Particulate matter formation	**Particulate matter formation**	**HH**	**Rest of HH**	**R**	Fantke et al. 2015; Humbert et al. 2011; Gronlund et al. 2015			Population density used as proxy of emission	5
Photochemical oxidant formation	**Photochemical oxidant formation**	**HH**	**Rest of HH**	**R**	European Commission, 2011	Not regionalized			134
Ionizing radiations	**Ionizing radiation, human health**	**HH**	**Water, HH**	**R**	Frischknecht et al. 2000; Margni et al. 2008; Garnier-Laplace et al. 2008	Not regionalized			29
	Ionizing radiation, ecosystem quality	**EQ**	**Water, EQ**	**R**					
Water scarcity*				**R**	Boulay et al. 2018 (AWARE)	Subwatershed		Water consumption in each native resolution cell included in the country / continent / Globe	1
	Water availability, human health	**HH**	**Water, HH**	**R**	Boulay 2011	Watershed & countries			58
	Water availability, resources & ecosystem services	*R&ES*		*I*	Boulay 2011; Cao et al. 2015	Watershed & countries			58
	Water availability, freshwater ecosystem	**EQ**	**Water, EQ**	**R**	Hanafiah et al. 2011	Watershed			1
	Water availability, terrestrial ecosystem	**EQ**	**Water, EQ**	**R**	van Zelm et al. 2011	Not regionalized			2
	Thermally polluted water	**EQ**	**Water, EQ**	**R**	Verones et al. 2010	Not regionalized			1
Water stream use and management	*Water stream use and management*	*EQ*		*I*	Humbert and Maendly 2009	Not regionalized			1
Land transformation, biodiversity	**Land transformation, biodiversity**	**EQ**	**Rest of EQ**	**R**	de Baan et al. 2013; Curran et al. 2010	Olson Biomes		Surface of the characterized land cover in the different sections of Olson ecoregions covering the country / continent / Globe	12
	Land transformation, mechanical filtration	*R&ES*		*I*	Cao et al. 2015; Saad et al. 2011; Curran et al. 2010	Holridge lifezones			
	Land transformation, phys.-chemical filtration	*R&ES*		*I*		Holridge lifezones			
	Land transformation, freshwater recharge	*R&ES*		*I*		Holridge lifezones			
	Land transformation, erosion resistance	*R&ES*		*I*		Holridge lifezones			
	Land transformation, biotic production	*R&ES*		*I*		JRC Climate zones			
	Land transformation, mechanical filtration	*HH*		*I*		Holridge lifezones			
	Land transformation, phys.-chemical filtration	*HH*		*I*		Holridge lifezones			
	Land transformation, freshwater recharge	*HH*		*I*		Holridge lifezones			
Land occupation, biodiversity	**Land occupation, biodiversity**	**EQ**	**Rest of EQ**	**R**	de Baan et al. 2013	Olson Biomes			6
	Land occupation, mechanical filtration	*R&ES*		*I*	Cao et al. 2015; Saad et al. 2011	Holridge lifezones			
	Land occupation, phys.-chemical filtration	*R&ES*		*I*		Holridge lifezones			
	Land occupation, freshwater recharge	*R&ES*		*I*		Holridge lifezones			
	Land occupation, erosion resistance	*R&ES*		*I*		Holridge lifezones			
	Land occupation, biotic production	*R&ES*		*I*		JRC Climate zones			
	Land occupation, mechanical filtration	*HH*		*I*		Holridge lifezones			
	Land occupation, phys.-chemical filtration	*HH*		*I*		Holridge lifezones			
	Land occupation, freshwater recharge	*HH*		*I*		Holridge lifezones			

The table below shows table 2 from the publication, which shows midpoint level impact category and the respective unit for characterosation, damagel level impact category and the respective unit for characterosiation, as well as calculation procedures for the fate factor, exposure factor, exposure reponse factor and severitify factor, when applicable.

Table 14: Overview of the midpoint- and damage level impact categories and their FF, XF, ERF and SF modelling, tqken from Bulle et al., 2019

Midpoint level impact category (* proxy midpoint)	Midpoint level characterization factor unit	Damage level impact category	Damage level characterization factor unit	Fate Factor FF (or competition scarcity index CSI)	Exposure Factor XF	Exposure Response Factor ERF	Severity Factor SF
Climate change, long-term*	$kg\ CO_{2\ eq(long)}/kg_{emitted}$			$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass in the atmosphere}}\,dt}{\text{Mass}_{\text{emitted}}}$	$\frac{\Delta_{\text{Temperature after 100 years}}}{\int_{t1}^{t2} \Delta_{\text{Mass in the atmosphere}}\,dt}$		
Climate change, shorter-term*	$kg\ CO_{2\ eq(shorter)}/kg_{emitted}$				$\frac{\int_{t1}^{t2} \Delta_{\text{Radiative forcing}}\,dt}{\int_{t1}^{t2} \Delta_{\text{Mass in the atmosphere}}\,dt}$		
	-	**Climate change, HH**	$DALY/kg_{emitted}$		$\frac{\int_{t_1}^{t_2} \Delta_{\text{Temperature}}\,dt}{\int_{t_1}^{t_2} \Delta_{\text{Mass in the atmosphere}}\,dt}$	$\text{Case}/\int_{t_1}^{t_2} \Delta_{\text{Temperature}}\,dt$	$\text{Damage}_{HH}/\text{Case}$
		Climate change, EQ	$PDF\cdot m^2\cdot yr/kg_{emitted}$			$\text{Damage}_{EQ}/\int_{t_1}^{t_2} \Delta_{\text{Temperature}}\,dt$	
		Climate change, R&ES	$\$/kg_{emitted}$		$\frac{\int_{t1}^{t2} \Delta_{\text{Radiative forcing}}\,dt}{\int_{t1}^{t2} \Delta_{\text{Mass in the atmosphere}}\,dt}$	$\text{Damage}_{R\&ES}/\int_{t_1}^{t_2} \Delta_{\text{Radiative forcing}}\,dt$	
	-	**Marine acidification**	$PDF\cdot m^2\cdot yr/kg_{emitted}$		$\frac{\int_{t_1}^{t_2} \Delta_{pH}\,dt}{\int_{t_1}^{t_2} \Delta_{\text{Mass in the atmosphere}}\,dt}$	$\text{PAF}\cdot\text{Area}\cdot\text{Time}/\int_{t_1}^{t_2} \Delta_{pH}\,dt$	$\text{Damage}_{EQ}/(\text{PAF}\cdot\text{Area}\cdot\text{Time})$
Ozone layer depletion	$kg\ CFC\text{-}11_{eq}/kg_{emitted}$	**Ozone layer depletion**	$DALY/kg_{mitted}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass eq eff.strato.chlorine}}\,dt}{\text{Mass}_{\text{emitted}}}$	$\frac{\text{UVB}_{\text{human exposure}}}{\int_{t_1}^{t_2} \Delta_{\text{Mass eq eff.strato.chlorine}}\,dt}$	$\frac{\text{Damage}_{HH}}{\text{UVB}_{\text{human exposure}}}$	
Mineral resources use	$kg_{deprived}/kg_{dissipated}$	*Mineral resources use*	$\$/kg_{dissipated}$	$\text{Mass}_{deprived}/\text{Mass}_{dissipated}$		$\text{Damage}_{R\&ES}/\text{Mass}_{deprived}$	
Fossil energy use	$MJ_{deprived}/kg_{dissipated}$	*Fossil energy use*	$\$/kg_{dissipated}$	$\text{Primary energy}_{deprived}/\text{Mass}_{dissipated}$		$\text{Damage}_{R\&ES}/\text{Primary energy}_{deprived}$	
Terrestrial acidification	$kg\ SO_{2\ eq}/kg_{emitted}$	**Terrestrial acidification**	$PDF\cdot m^2\cdot yr/kg_{emitted}$	$\frac{\text{Mass}_{\text{deposited}}}{\text{Mass}_{\text{emitted}}}$	$\frac{\int_{t_1}^{t_2} \Delta_{pH}\,dt}{\text{Mass}_{\text{deposited}}}$	$\text{PAF}\cdot\text{Area}\cdot\text{Time}/\int_{t_1}^{t_2} \Delta_{pH}\,dt$	DamageEQ/ (PAF · Area · Time)
Freshwater acidification	$kg\ SO_{2\ eq}/kg_{emitted}$	**Freshwater acidification**	$PDF\cdot m^2\cdot yr/kg_{emitted}$				
Marine eutrophication	$kg\ N\ N\text{-}lim\ eq/kg_{emitted}$	**Marine eutrophication**	$PDF\cdot m^2\cdot yr/kg_{emitted}$		$\text{PDF}\cdot\text{Area}\cdot\text{Time}/\text{Mass}_{\text{deposited}}$		$\text{Damage}_{EQ}/\text{PDF}\cdot\text{Area}\cdot\text{Time}$
Freshwater eutrophication	$kg\ PO_4\ P\text{-}lim\ eq/kg_{emitted}$	**Freshwater eutrophication**	$PDF\cdot m^2\cdot yr/kg_{emitted}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\,dt}{\text{Mass}_{\text{emitted}}}$	$\text{PAF}\cdot\text{Area}\cdot\text{Time}/\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\,dt$		$\text{Damage}_{EQ}/\text{PAF}\cdot\text{Area}\cdot\text{Time}$

Midpoint level impact category (* proxy midpoint)	Midpoint level characterization factor unit	Damage level impact category	Damage level characterization factor unit	Fate Factor FF (or competition scarcity index CSI)	Exposure Factor XF	Exposure Response Factor ERF	Severity Factor SF
Freshwater ecotoxicity	$CTUe/kg_{emitted}$	**Freshwater ecotoxicity**	$PDF\cdot m^2\cdot yr/kg_{emitted}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\,dt}{\text{Mass}_{\text{emitted}}}$	$\frac{\text{Mass}_{\text{bioavailable}}}{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\,dt}$	$\frac{\text{PAF}\cdot\text{Volume}\cdot\text{Time}}{\text{Mass}_{\text{bioavailable}}}$	$\text{Damage}_{EQ}/\text{PAF}\cdot\text{Volume}\cdot\text{Time}$
	-	*Terrestrial ecotoxicity*					
		Marine ecotoxicity					
Human toxicity cancer	$CTUh/kg_{emitted}$	**Human toxicity cancer**	$DALY/kg_{emitted}$		$\frac{\text{Mass}_{\text{intake}}}{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\,dt}$	$\frac{\text{Case}}{\text{Mass}_{\text{intake}}}$	$\text{Damage}_{HH}/\text{Case}$
Human toxicity non-cancer	$CTUh/kg_{emitted}$	**Human toxicity non-cancer**					
Particulate matter formation	$kg\ PM2.5_{eq}/kg_{emitted}$	**Particulate matter formation**					
Photochemical oxidant formation	$kg\ NMVOC_{eq}/kg_{emitted}$	**Photochemical oxidant formation**					
Ionizing radiations	$Bq\ C\text{-}14_{eq}/kg_{emitted}$	**Ionizing radiation, HH**					
		Ionizing radiation, EQ	$PDF\cdot m^2\cdot yr/kg_{emitted}$		$\frac{\text{PAF}\cdot\text{Volume}\cdot\text{Time}}{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\,dt}$		$\text{Damage}_{EQ}/\text{PAF}\cdot\text{Volume}\cdot\text{Time}$
Water scarcity *	$m^3_{world\text{-}eq}/m^3_{consumed}$		-	Increased relative deprivation potential/ $\text{Volume}_{consumed}$			
	-	**Water availability, HH**	$DALY/m^3_{consumed}$	$\text{Volume}_{deprived}/\text{Volume}_{consumed}$	$\text{Volume}_{\text{lost with no adaptation}}/\text{Volume}_{deprived}$	$\text{Damage}_{HH}/\text{Volume}_{\text{lost with no adaptation}}$	
		Water availability, R&ES	$\$/m^3_{deprived}$	$\text{Volume}_{deprived}/\text{Volume}_{consumed}$	$\text{Volume}_{\text{lost with adaptation}}/\text{Volume}_{deprived}$	$\text{Damage}_{R\&ES}/\text{Volume}_{\text{lost with adaptation}}$	
		Water availability, freshwater ecosystem	$PDF\cdot m^2\cdot yr/m^3_{dissipated}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{river discharge}}\,dt}{\text{Volume}_{\text{dissipated}}}$	$\text{PAF}\cdot\text{Volume}\cdot\text{Time}/\int_{t_1}^{t_2} \Delta_{\text{river discharge}}\,dt$		$\text{Damage}_{EQ}/\text{PAF}\cdot\text{Volume}\cdot\text{Time}$
		Water availability, terrestrial ecosystem	$PDF\cdot m^2\cdot yr/m^3_{dissipated}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{groundwater depth}}\,dt}{\text{Volume}_{\text{dissipated}}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{soil moisture}}\,dt}{\int_{t_1}^{t_2} \Delta_{\text{groundwater depth}}\,dt}$	$\frac{\text{PNOF}}{\int_{t_1}^{t_2} \Delta_{\text{soil moisture}}\,dt}$	$\frac{\text{Damage}_{EQ}}{\text{PNOF}}$
	-	**Thermally polluted water**	$PDF\cdot m^2\cdot yr/m^3_{cooling\ water}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{river temperature}}\,dt}{\text{Volume}_{\text{cooling water}}}$	$\text{PDF. Volume. time}/\int_{t_1}^{t_2} \Delta_{\text{river temperature}}\,dt$		$\text{Damage}_{EQ}/\text{PDF}\cdot\text{volume.time}$
Water stream use and management	$m_{eq}^3/m^3_{turbined}$	*Water stream use and management*	$PDF\cdot m^2\cdot yr/m^3_{turbined}$	$\text{Damage}_{EQ}/m^3_{turbined}$			

Midpoint level impact category (* proxy midpoint)	Midpoint level characterization factor unit	Damage level impact category	Damage level characterization factor unit	Fate Factor FF (or competition scarcity index CSI)	Exposure Factor XF	Exposure Response Factor ERF	Severity Factor SF
Land transformation, biodiversity	$m^2_{arable\ land\ eq}/m^2_{transformed}$	**Land transformation, biodiversity**	$PDF \cdot m^2 \cdot yr/m^2_{transformed}$	$\frac{Area_{occupied} \cdot Time}{Area_{transformed}}$	$\frac{Damage_{EQ}}{Area_{occupied} \cdot Time}$		
	-	*Land transformation, mechanical filtration, R&ES*	$\$/m^2_{transformed}$	$\frac{\int_{t_1}^{t_2} \Delta_{biophysical\ indicator}\, dt}{Area_{transformed}}$	$\frac{\int_{t_1}^{t_2} Service_{not\ lost\ (adaptation)}\, dt}{\int_{t_1}^{t_2} \Delta_{biophysical\ indicator}\, dt}$	$Damage_{R\&ES} / \int_{t_1}^{t_2} Service_{not\ lost\ (adapt.)}\, dt$	
		Land transformation, phys.-chemical filtration, R&ES					
		Land transformation, freshwater recharge, R&ES					
		Land transformation, erosion resistance, R&ES					
		Land transformation, biotic production, R&ES					
		Land transformation, mechanical filtration, HH	$DALY/m^2_{transformed}$		$\frac{\int_{t_1}^{t_2} Service_{lost\ (no\ adaptation)}\, dt}{\int_{t_1}^{t_2} \Delta_{biophysical\ indicator}\, dt}$	$Damage_{HH} / \int_{t_1}^{t_2} Service_{lost\ (no\ adapt.)}\, dt$	
		Land transformation, phys.-chemical filtration, HH					
		Land transformation, freshwater recharge, HH					
Land occupation, biodiversity	$m^2_{arable\ land\ eq} \cdot yr/(m^2_{occupied} \cdot yr)$	**Land occupation, biodiversity**	$PDF \cdot m^2 \cdot yr/(m^2_{occupied} \cdot yr)$	$\frac{Damage_{EQ}}{Area_{occupied} \cdot Time}$			
	-	*Land occupation, mechanical filtration, R&ES*	$\$/m^2_{transformed}$	$\frac{\int_{t_1}^{t_2} \Delta_{biophysical\ indicator}\, dt}{Area_{Occupied} \cdot Time}$	$\frac{\int_{t_1}^{t_2} Service_{not\ lost\ (adaptation)}\, dt}{\int_{t_1}^{t_2} \Delta_{biophysical\ indicator}\, dt}$	$Damage_{R\&ES} / \int_{t_1}^{t_2} Service_{not\ lost\ (adapt.)}\, dt$	
		Land occupation, phys.-chemical filtration, R&ES					
		Land occupation, freshwater recharge, R&ES					
		Land occupation, erosion resistance, R&ES					
		Land occupation, biotic production, R&ES					
		Land occupation, mechanical filtration, HH	$DALY/m^2_{transformed}$		$\frac{\int_{t_1}^{t_2} Service_{lost\ (no\ adaptation)}\, dt}{\int_{t_1}^{t_2} \Delta_{biophysical\ indicator}\, dt}$	$Damage_{HH} / \int_{t_1}^{t_2} Service_{lost\ (no\ adapt.)}\, dt$	
		Land occupation, phys.-chemical filtration, HH					
		Land occupation, freshwater recharge, HH					

Note that $t_1 = 0$ and $t_2 = 100$ years for shorter-term indicators; $t_1 = 100$ years and $t_2 = \infty$ (500 years for climate change) for long-term damage level indicators; $t_1 = 0$ and $t_2 = 100$ years for the two climate change midpoint indicators; and $t_1 = 0$ and $t_2 = \infty$ for all the other indicators

HH human health, *EC* ecosystem quality, *R&ES* resources & ecosystem services

Through the reaction of CO_2 in the atmosphere with water, carbonic acid is formed in oceans. The dissociation of the carbonic acid results in acidification of the marine environment through the increase of H+ ions. The authors of IMPACT World+ therefore argue that the fate modelling of marine acidification should be consistent with the climate change modelling. Therefore, the exposure factor of marine acidification is related to the increase in CO_2 concentration in the atmosphere. The effect factor is then based on a species sensitivity distribution (SSD) curve using the H+ concentration at which 50% of the population of 50% of the considered species are affected ($HC50_{EC50}$) (Azevedo et al. 2015). The data reported by Azevedo et al. (2015) is obtained from 72 studies comprising 246 experiments and encompasses 82 calcifying marine species. The IMPACT World+ method assumes a linear response between 0 and $HC50_{EC50}$ of the SSD curve to be consistant with effect factors for ecotoxicity obtained from SSD curves used in USEtox. The native resolution is the global scale and encompasses 9 elementary flows.

Damages on ecosystems for acidification (terrestrial and freshwater) are obtained by combining midpoint CFs with an effect factor (Roy et al. 2014a, Roy et al. 2014b). Terrestrial acidification focusses on the change in casular plant speices responding to a change in soil pH, whereas freshwater acidification the disappearance of fish species is linked to changes in water pH. The underlying data for the terrestrial acidification is obtained from Azevedo et al. (2013), in which logistic regression curves are used to estimate species richness-pH response curves for 6 biomes, encompassing 2409 species obtained from 140 studies. For terrestrial and freshwater acidification, the native geographical resolution is 2° x 2,5° and includes 15 elementary flows. Marine eutrophication encompasses the same native geographical scope however includes 16 elementary flows. Freshwater eutrophication on the otherhand has a native geographical resolution of 0,5° x 0,5° and encompasses 8 elementary flows based on work performed (Helmes et al. 2012, Tirado-Seco

2005). For freshwater ecotoxicity, the native geographical scale is the continental level and encompasses 2516 elementary flows. Freshwater ecotoxicity uses USEtox midpoint level CFs to estimate the potentially affected fraction of the exposed ecosystem species. Through the integration over time and water volume and applying an assumed severity factor of 0,5 results in the potentially disappeared fraction of species. The impacts of water availability on freshwater ecosystems has a native geographical resolution at the watershed level, encompasses 1 elementary flow and is modelled based on Hanafiah et al (2011). The impact of water availability on terrestrial ecosystems is not regionalized, encompasses 2 elementary flows and is modelled based on van Zelm et al (2011). Thermally polluted water is based on the model of Verones et al. (2010) which is not regionalized and encompasses 1 elementary flow.

8.3 LC-IMPACT – Calculation of ecosystem quality CF, exemplarily from land use

In Table 15, there is an overview which taxonomic groups are included in LC-IMPACT.

Table 15: LC-IMPACT – Overview of included taxonomic group for calculating maps of species counts and vulnerability scores. FEOW stands for freshwater ecoregions of the world. (Verones et al. 2020b)

Environmental mechanism	taxonomic group	taxonomic classification	Spatial resolution	VS map available?	Data origin
Acidification	Tracheophyta	Phylum	0.53°x0.53°	no, species numbers used as proxy	Kier et al. (2009)
Freshwater eutrophication	Fish	Classes	FEOW	no, fish richness density and total fish number used as proxy	Abell et al. (2008)
Marine eutrophication	Lobsters, bony fish, cartilaginous fish and sea cucumbers	Classes (note: only species occurring in marine neritic habitats are included)	Large Marine Ecosystems	yes	IUCN (2018)
Photochemical ozone formation	Tracheophyta	Phylum	0.53°x0.53°	no	Kier et al. (2009)
Water	Mammalia Aves Amphibia Reptilia	Classes	0.05°x0.05°	yes	IUCN (2018)
Land	Mammalia Aves Amphibia Reptilia Tracheophyta	Classes	0.05°x0.05°	yes	IUCN (2018)
Climate change	Global average	-	-	no	
Ecotoxicity	Tracheophyta Freshwater Fish Lobsters, bony fish, cartilaginous fish and sea cucumbers	Classes/Phylum	-	No, proxies used. Terrestrial:species numbers tracheophyta; freshwater: fish numbers; marine: species numbers Lobsters, bony fish, cartilaginous fish and sea cucumbers	Abell et al. (2008); Kier et al. (2009); IUCN (2018)

8.4 BioMAPS

This Annex provides additional information on the BioMAPS methodology. it starts by discussing the nomenclature used for land use flows in the methodology, followed by a description of the approaches used for the global, local and regional scale. This annex also provides a brief discussion of several aspects in the BioMAPS methodology, for those interested. Finally, some figures from the methodology are included to provide additional information on the indicators which can be used in the local scale of the assessment as well as a decision tree on the application of the BioMAPS method.

Land use flow nomenclature

Due to the change in the structure of the LCI, the method proposes an extended list of land use flows which is able to reflect the multi-scale approach described above. BioMAPS proposes to use a land use nomenclature based on the flow properties that define a land use type. The proposed nomenclature seperates land use flows based on so-called flow properties such as land use type specific set of management parameters, land use intensity and its geolocation. These aspects are defined and calculated in a GIS environment and directly linked to the LCIA method. The BioMAPS land use flow nomenclature is shown in the table below for cropland and pasture, the same approach is applied for each land use type.

Table 16: Land use flow nomenclature based on flow properties in BioMAPS (Maier 2023)

Level 1	Level 2	Flow properties			
Land use type	Land use subtype	Land use intensity	Land use intensity value	Management parameters	Geolocation
Cropland	C3 nitrogen-fixing	Minimum	0.2	E.g. not fertilized, low mechanization	E.g. Finland
Pasture	Rangeland	Light	0.5	E.g. medium livestock intensity, no pesticides, high mechanization rate	E.g. Iceland

The first two levels of the land use flow nomenclature resemble those used by Chaudhary (Chaudhary & Brooks 2018), which are based on the land use impact model of the PREDICTS database. The nomenclature is extended by applying the land use model of Hurtt (Hurtt et al. 2011), which categorises 12 different land use classes and subclasses. To align the land use classes between the varous sources, some subclasses have been aggregated into land use classes. The classifications are expanded with flow properties, such as intensity (minimum, light, intense) as well as a intensity gradient (ranging from 0 to 1), which is derived from specific land management practices and the geolocation (see table above). This enables the BioMAPS method to use a finite number of land flows, with infite property combinations in the impact assessment. To enhance the implemantion of the BioMAPS method in existing LCA software and the LANCA model, the nomenclature is matched to current ILCD land use flows.

In summary, to apply the BioMAPS method, additional information in the inventory may be requied, although the method can also provide information on general cases. For example, land use management practices can be included in the inventory, which subsequently impacts the local spatial scale of the method, as seen in the figure below. The overview of the input required is visualized in the figure below. Each of the different spatial resolutions of the biodiversity risk are discussed below in more detail.

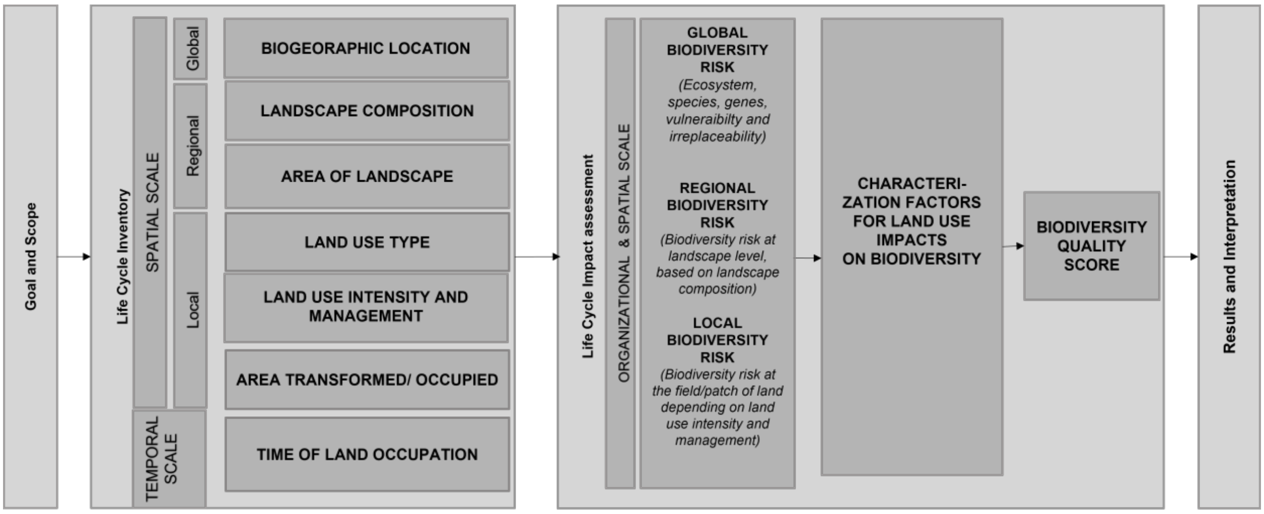

Figure 11: Overview of Life Cycle Inventory of the BioMAPS method (Maier 2023)

Generation of the global risk map

In the development of the unified biodiversity risk map, three world maps are created; a proactive global risk map identifying areas with a low vulnerability, a reactive global risk map identifying areas of high vulnerability and the unified biodiversity risk map combining the two maps. To achieve this, the method analyses existing conservation databases and schemes are anaylsed for suitability and classified in reactive conservation schemes, proactive conservation schemes and irreplaceable schemes. The reactive schemes aim to capture biodiversity hotspots where endemic species and large habitat losses have been lost, indicating a high vulnerability to biodiversity loss. Proactive schemes focus on capturing pristine and intact ecosystems, indicating little loss of biodiversity. Finally, irreplaceable schemes focus on measuring common taxa of endemic species, such as birds, plants or vertebrates. Higher number of endemic species in a region indicate higher risks of critical biodiversity loss due to changes in the ecosystem. In total, 10 different conservation schemes have been included in the making of the unified biodiversity risk map. Examples of schemes included in the process are: Key Biodiversity Areas, Biodiversity Hotspots, Intact Forest Landscapes, Global 200 ecoregions, Alliance for Zero Extinction, Evolutionarily Distinct and Globally Endangered.

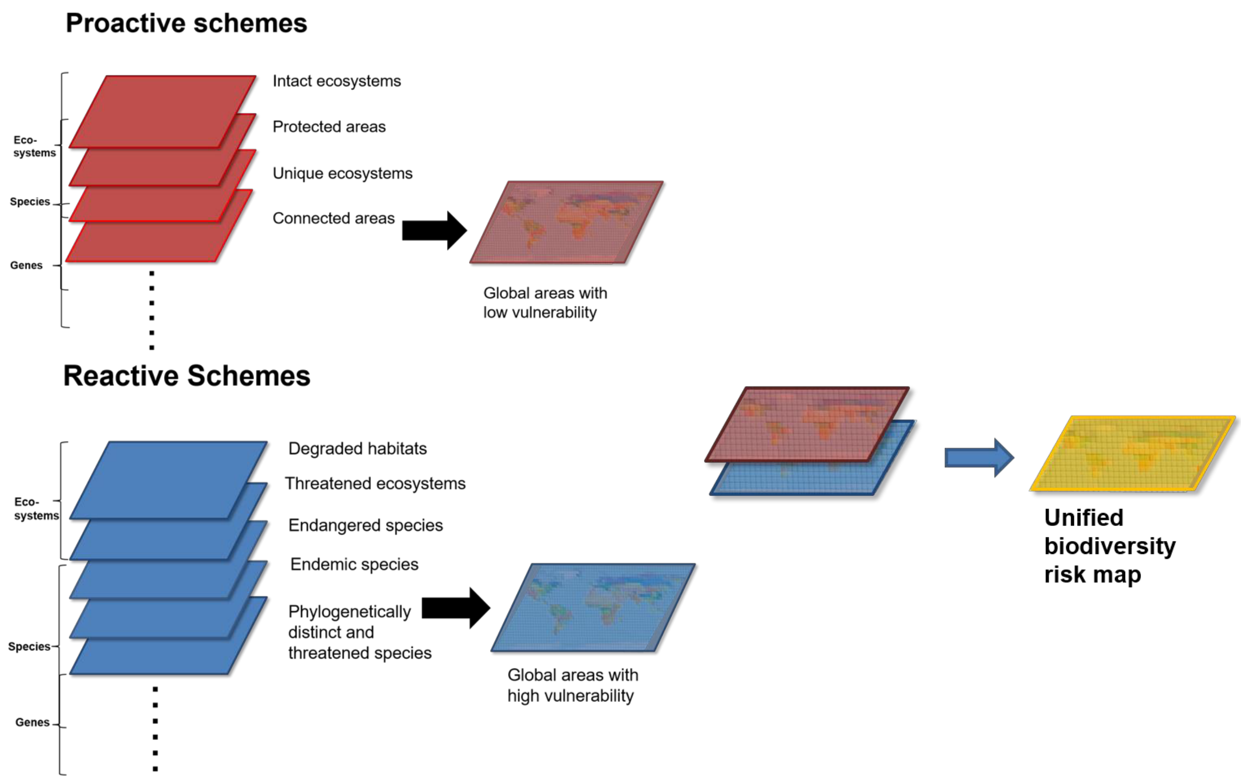

Figure 12: Overview of the generation of the unified biodiversity risp map (Maier 2023)

Of the 10 global conservation schemes considered, three fall into the proactive classification, indicating most focus on the reactive approach of biodiversity conservation. These schemes often focus on species above ecosystem and genetic biodiversity. Two schemes consider the genetic aspects, which are the CPD and the EDGE sites. Conservation schemes focussing on irreplaceability are integrated within the reactive risk map. The data is processed using GIS, resulting in the generation of two risk maps indicating global areas with low and high vulnerability. These two maps are combined obtaining the Unified Biodiversity Risk Map (UBR map). This approach, however, still leaves around 20% of the terrestrial area not covered by any risk area, as no conservation schemes are present for these areas. To fill these gaps, a Jenkins biodiversity value is calculated to fill the gaps (Jenkins et al. 2013). The Jenkins biodiversity value is obtained by calculating the total number of threatened mammals, birds and amphibians as well as the total number of endemic species and total number of species. By calculating the proportions of species per grid cell for each dataset and averaging the proportions per grid cell, a single value between 0 and 1 is found, which is the Jenkins biodiversity value. This approach is used to fill the gaps in the UBR map, thus completing it.

Next, the BioMAPS regionalises the global risks by land use type using land use models of Hurtt et al. (2011). This is achieved by determining the overlapping area of the individual land use types in proactive and reactive areas and dividing it by the total area of the land use type per analytical unit (grid cell and country). The approach distinguishes 4 different land use flows and 8 subflow;

- Crop land (C3 perennials, C3 annuals, C4 perennials and C4 annuals, and C3 nitrogen fixing plants
- Forestry (primary vegetation forest, and secondary vegetation forest

- Pasture land (managed pastures, and pastures
- Urban areas

For each land use flow, a uniform map is produced as the sum of all subtypes and the biodiversity risk map is used to calculate the overlap. This approach is also applied for the average change of historical and future land flows, resulting in maps which show the proportion of a land use type corresponding to risk sites for biodiversity. These results can be used when the coordinates of the region are known, if the land use is known or on a country level, which then shows the percentage of land use which overlaps with risk areas for biodiversity. This approach is also applied for the Jenkins Index, when the area is not covered by the UBR map.

The regionalisation of land use transformation is performed by considering all possible variations from one type of land use to another, again using land use model of Hurtt et al. (2011), which provides various scenarios for land transformation. In the BioMAPS method, the SSP5 scenario of the IPCC is used for the regionalisation of the transformation flows. The SSP5 scenario is described as a conservative development path, aligning with the LCA practice of making conservative assumptions when data availability is low.

With all generated maps, the final global risk factor for each land use flow can be calculated as all areas are covered by atleast one of the maps. This is achieved by calculating the probability of land use in risk areas, the proportion of risk areas per grid cell and the Jenkins index value for areas outside of biodiversity risk areas, resulting in a dimensionless map of global risks per land use flow. The map produces risks from 0 to 1, and country level risks are also generated from this map per land use flow. The risk factors are not normalised, as conservation scientists suggest global biodiversity loss has a higher implication compared to local or regional biodiversity loss.

Local scale

The local scale of biodiversity risks in the BioMAPS method encompasses land use type specific intervals for various ecological indicators, applicable per land use type. The approach includes the calculation of the Land Use Intensity indices (LUI) by identifying and using biodiversity specific management parameters. These are translated into land use type specific intervals from which global datasets for biodiversity risk values at local scale are obtained depending on the land use intensity.

The PREDICTS database and methods used by Newbold et al. (Hudson et al. 2014, Newbold et al.2015, 2016), are used to derive biodiversity indicators of different types of land use, so that the individual indicators can be calculated and summarised in a local biodiversity risk index. The local scale assess the biodiversity risk quality index of current land use type with a reference situation, which is primary vegetation in both Newbold et al. and PREDICTS (Hudson et al. 2014, Newbold et al.2015, 2016). Permanent transformation is included by comparing the average biodiversity quality between two different land use types, based on formulaes of the UNEP-SETAC Framework. The data of Newbold includes information for indicator species richness, abundance and rarefaction as well as the intensity classes per land use type. As such, the data provides an interval of biodiversity risk, which the BioMAPS method converts to a local biodiversity risk based on the LUI index for all land use types. Through this approach, land management is incorporated in the final local risk value, as the management practices determine the intensity, which in turn determines where the local biodiversity impact is on the interval derived from the PREDICTS model.

To calculate the land use intensities from management practices, a distinction is made between management parameters attributable to the patch and/or field itself or to the landscape. In case the practice is attributed to the landscape, it is covered in the regional scale (see below). Measures related to the patch itself are included in the LUI calculation and are identified based on the Conservation Evidence Database by Sutherland et al (2018), using an approach similar to Ulrich et al. (2020). From the Conservation Evidence Database, only management activities which have been proven to be effective are selected, grouped and matched to the corresponding land use flow used in BioMAPS. Management activities related to policies, regulations, awareness and education are excluded, as are threats related to climate change. For each land use type, the management parameters are linked to drivers of biodiversity loss (climate change, habitat change, overexploitation, pollution and invasion of alien species), followed by the linking of the management parameter to management activities, based on the Conservation Evidence Database. In the next step, suitable indicators are identified to measure the impact of the management parameter on biodiversity, including describing whether the parameter is a pressure or relief. Finally, globally available datasets are used to quantify the LUI index. The figure below details the approach for the land use type cropland.

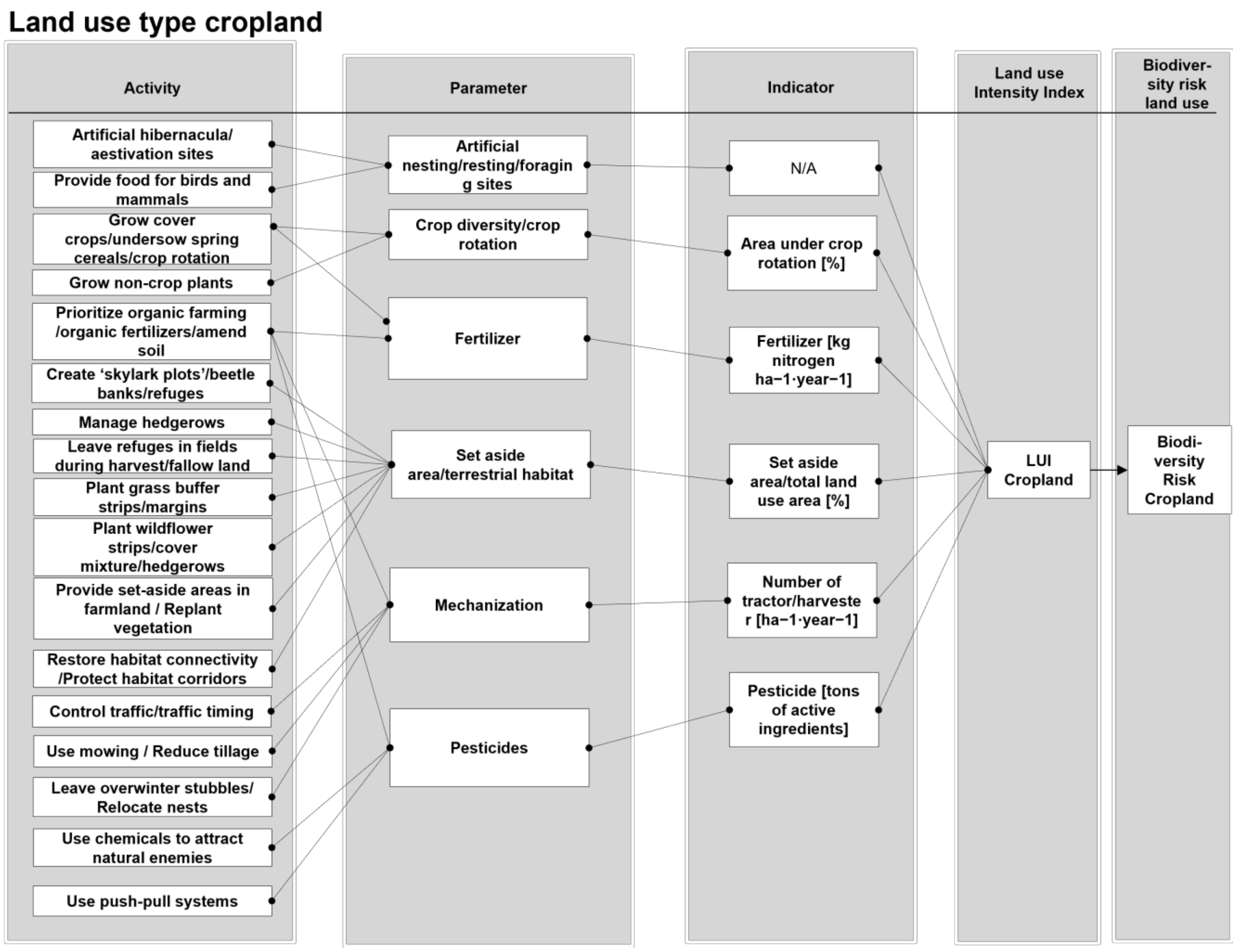

Figure 13: Management activites, parameters and indicators for cropland land use type (Maier 2023)

The authors note that not each indicator has a globally available dataset which can be used, identifying the need for further research and data generation to improve the method. The table below shows which datatypes are used for the calculation of the LUI of croplands and plantations. Other land use types ave other indicators and therefore also require other data. For information on the indicators and datatypes used for other land use types, see the BioMAPS methodology chapter 5.2.5 (Maier 2023).

Table 17: Indicators and data type used for crop land management activities (Maier 2023)

Management parameter	Indicator [unit]	Data type
Fertilizer	Fertilizer application rates [kg_N/(ha*a)]	Global maps, primary data
Pesticide	Pesticide application rates [$t_{active\ ingredients}$/(ha*a)]	Global maps, FAO statistics, primary data
Mechanization (tillage)	Number of machines [$No_{tractor/harvester}$ /(ha*a)]	FAO statistics, primary data
Set-aside areas/ecotones	Set-aside area per field area [%]	Primary data, satellite images
Crop rotation/crop diversity	Share crop rotation per field [%]	Global map, primary data
Global cropland data set	Area of cropland production [km²]	Global map, primary data

Each of the indicators is converted to a value between 0 and 1, for each of the land use subclasses, based on global maps per grid cell in the global map. Since each indicator is calculated differently, the calculation methods for the individual indicators are not detailed here, for more information see the BioMAPS methodology chapter 5.2.5 (Maier 2023.). To calculate the LUI of cropland, the following formula is applied;

$$LUI_{cropland[i]} = \frac{F[i]}{F[MTI]} + \frac{Me[i]}{Me[MTI]} + \frac{P[i]}{P[MTI]} + \frac{Area\ crop\ rotation}{total\ crop\ area} + \frac{set\ aside\ area}{total\ crop\ area}$$

In the formula above, LUI is the Land use intensity index for cropland at location i, F(i)/F(MTI) is the intensity of fertilizer application at location i, similarly Me(i)/Me(MTI) is related to the intensity of mechanization and P(i)/P(MTI) is related to the pesticide application intensity. Similar formulas are generated for each land use type. In the formula above, the individual terms in the equation are obtained from the normalised values of the indicators at the evaluated location. To convert the LUI into biodiversity risks, the risk invervals reported in the PREDICTS databased are interpolated by fitting equations to the three points of intensity reported (minimum, light, intensive) and the associated risk value of biodiversity derived from Newbold et al. (2015 & 2016). This procedure is applied for each type of land use.

Regional scale

To assess the biodiversity impact on regional scale, the LUI indices obtained above are used to calculate the Landscape Development Index (LDI), and include the management parameters which are applicable in a landscape context. Management parameters included in the LDI include for example primary habitat set aside, and restauration and set aside secondary habitats. The LDI is calculated by assessing the composition of land use types and subclasses provided by Hurtt et al. (2011), and multiplying each land use type with the LUI, resulting in a LDI per grid cell on the global map. The model developed by Hurtt et al. include information on the shares of primary and secondary vegetation, which is considered as set-aside land in the BioMAPS method. It should be noted that non-forest primary and secondary vegetation land use types, the lowest LUI intensity is assigned, with the argument that there is very little non-forest landscapes which are left "untouched". Land areas which are bare areas and desserts are not included as the method aims toprovide relevant information in product context.

Discussion and additional insights

the BioMAPS method provides a multi-scale method providing information on the origin, cultivation methods and influence of management strategies in the field and landscape in a product context. The method enables comparison between alternatives by quantifying potential risks for biodiversity on a global, regional and local scale. It quantifies the risks by combining databases, concepts and methods from different disciplines, aiming to bridge some of the gaps between ecology, conservation and LCA, considering the state-of-the-art in each discipline. Through this approach, it provides characterisation factors along an intensity gradient, allowing the evaluation of different land use types and intensities. It also enables the analysis of potential impacts on biodiversity at different spatial and organisational levels, aiming to support decision makers with the choice of production sites, raw material sourcing, cultivation methods and landscape design. Furthermore, the method is globally applicable while including regional and local management parameters, enabling the evaluation of value chains, which include both background data (land use type and country) and primary data (i.e. land use practices in the foreground system of a LCA). Finally, through the interdisciplinary approach linking LCA, geoscience, ecology and conservation, it bridges gaps traditionally not considered in LCA. The author also claims that the hierarchical structure of the method enables the integration of the method into existing life cycle impact assessment methods.

Nonetheless, the method has some limitations. One of the limitations of the method is the reliance of the method on global data sets, which presents several limitations on itself. Firstly, global datasets often lack information on uncertainty and contain inherent uncertainty and estimates based on the modelling approach and input data. Due to limited availability of global datasets, the same datasets are often included for various modelling approaches, risking autocorrelation. Furthermore, it can be debated if the approach to weight the global biodiversity risk more severe than the regional and local biodiversity risk has merrit.
Secondly, the calculation of the LUI results from disaggregated national statistics for some management parameters (mechanisation and pesticide use for example), increasing the uncertainty. Furthermore, specific information is often lacking, for example information on exactly which crop is grown or the toxicity of specific pesticides. The management parameters included in the model are all equally weighted, whereas their impact on biodiversity may not be equal. As such, the method includes several simplification which can be improved as soon as more specific data becomes availalbe. However, a trade-off between global applicability and accuracy is often identified. As such, the author recommends using the method for background assessments, while searching for primary data to obtain more accurate results.
Through using indicators which serve as a "basket of indicators" (meaning the combination of various indicators in one indicator), the risk of regression towards the mean increases when using too many indicators. The BioMAPS proposes the use of 5 indicators per index to minimise this risk. Nonetheless, the risk of double counting may not always be avoidable as various organisational scales cannot be fully separated. Moreover, relationships between the various metrics are not considered (higher use of fertiliser and pesticide may have a relationship with the level of mechanisation). The method also includes species richness and rarefied species richness, possibly putting more emphasis on species richness as a whole.

The relationship between the biodiversity risk and the land use intensity is based on the interpolation of three fixed points using polynomals, although ecological studies have found different types relationships, influenced by the ecological indicators used and the management practices to measure land use intensity.

This limitation presents a lack of knowledge. Finally, the use of country averages for the LDI may be misleading as country-wide landscape is hardly influenced by a single landowner.

Many of the limitations discussed above can be mitigated by further research and including the findings within the model. For example the effectiveness of the management parameters can be weighted when the effectiveness has been s cientifically proven. Also the relationship between the land use intensity, management parameters and the biodiversity risks can be improved when such such studies become available. Finally, it should be noted that the BioMAPS focusses on the influence on land use, which presents one of the main drivers of biodiversity loss, however the method does include, for example, the influence of climate change on changing ecosystems which present a risk for biodiversity.

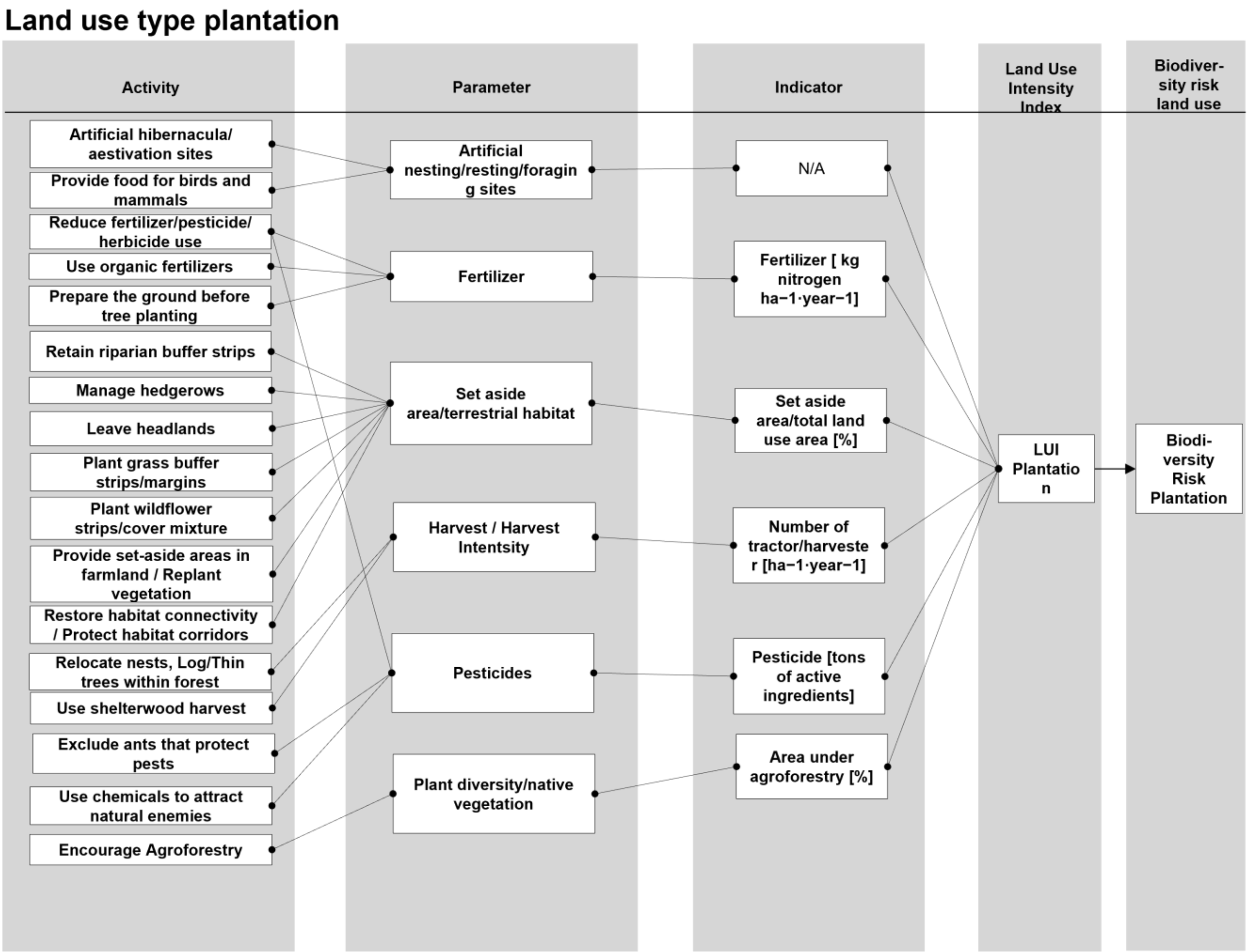

Figure 14: Management activites, parameters and indicators for plantation land use type (Maier 2023)

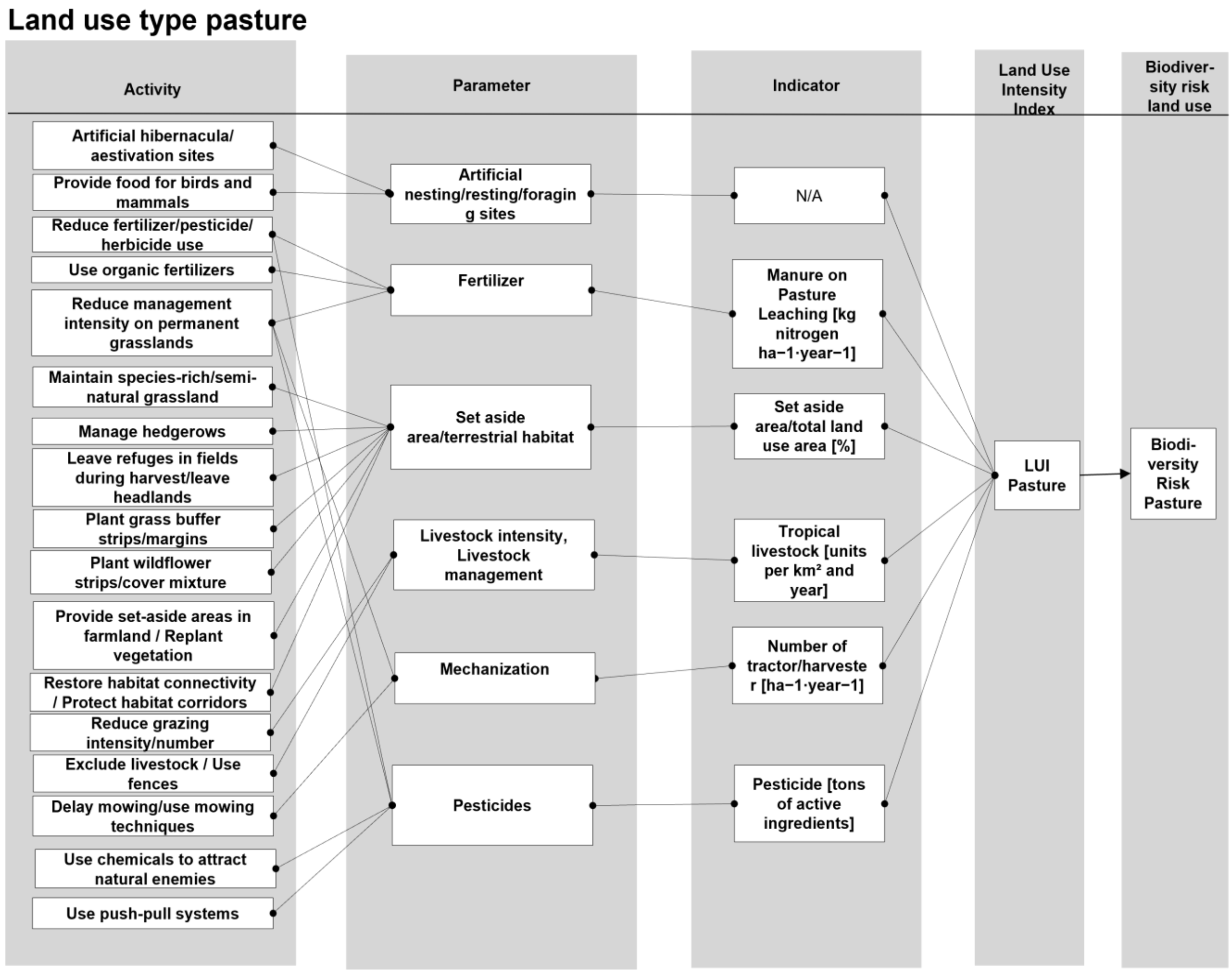

Figure 15: Management activites, parameters and indicators for Pasture land use type (Maier 2023)

Land use type urban

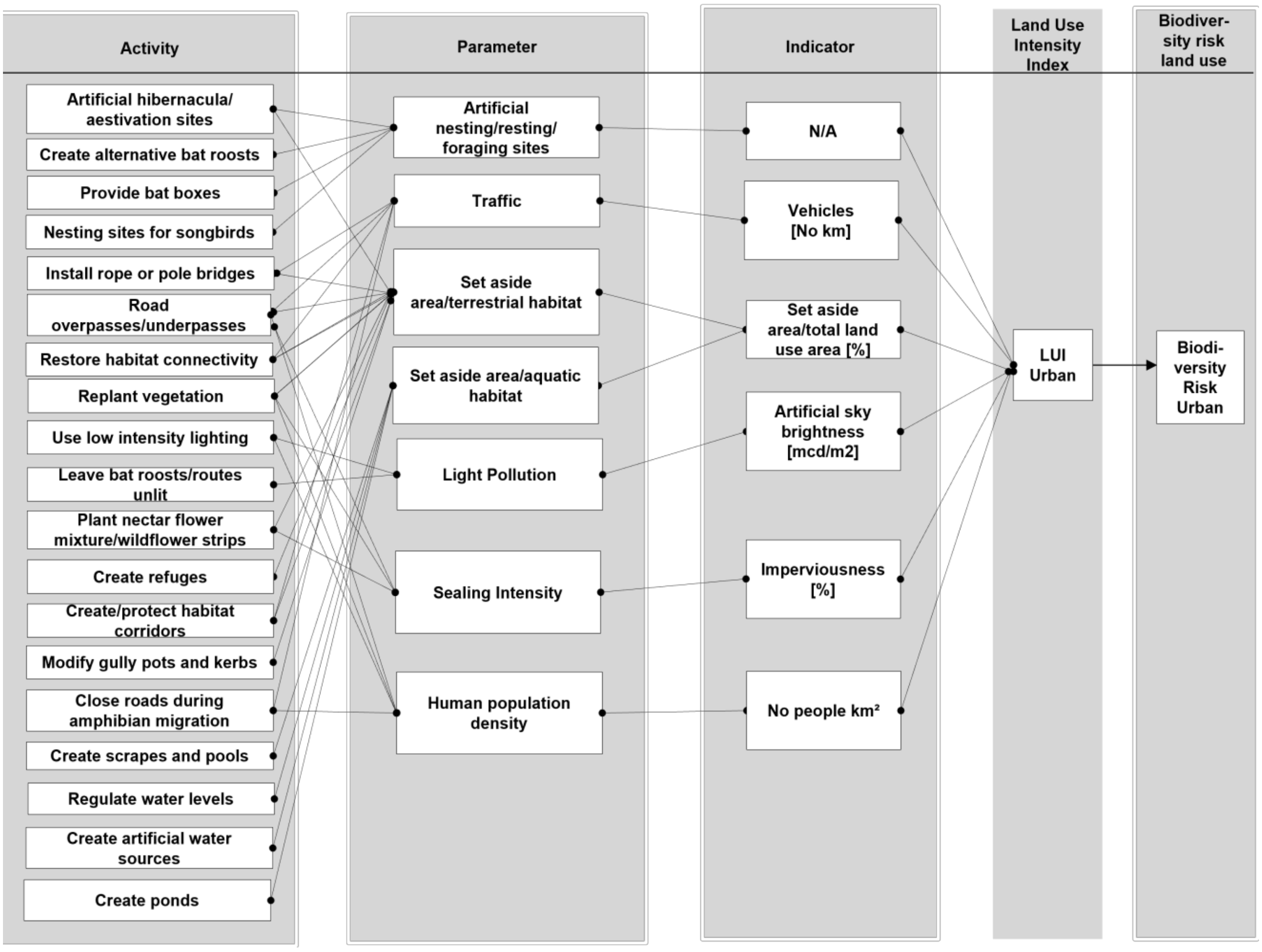

Figure 16: Management activites, parameters and indicators for urban land use type (Maier 2023)

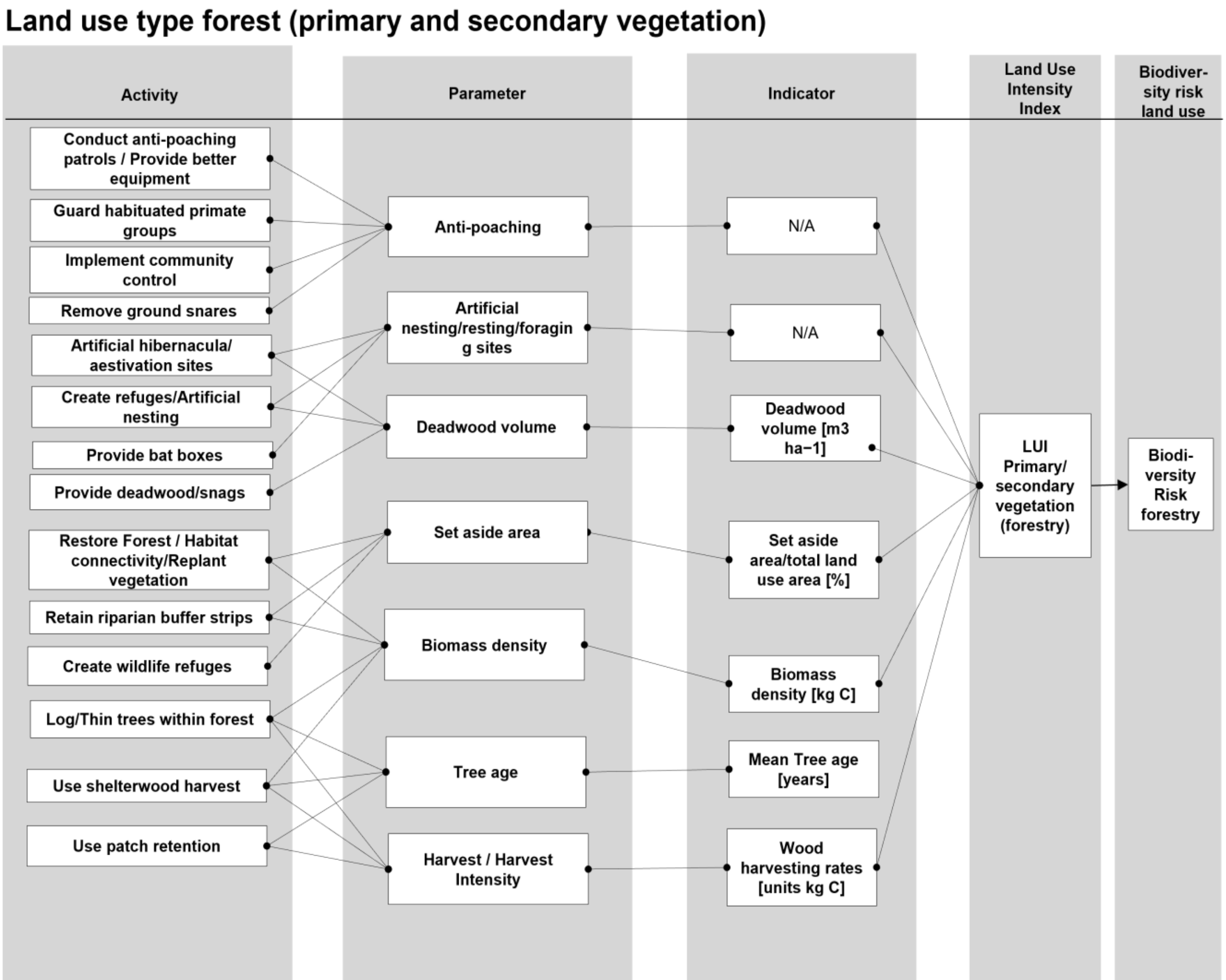

Figure 17: Management activites, parameters and indicators for forestry land use type (Maier 2023)

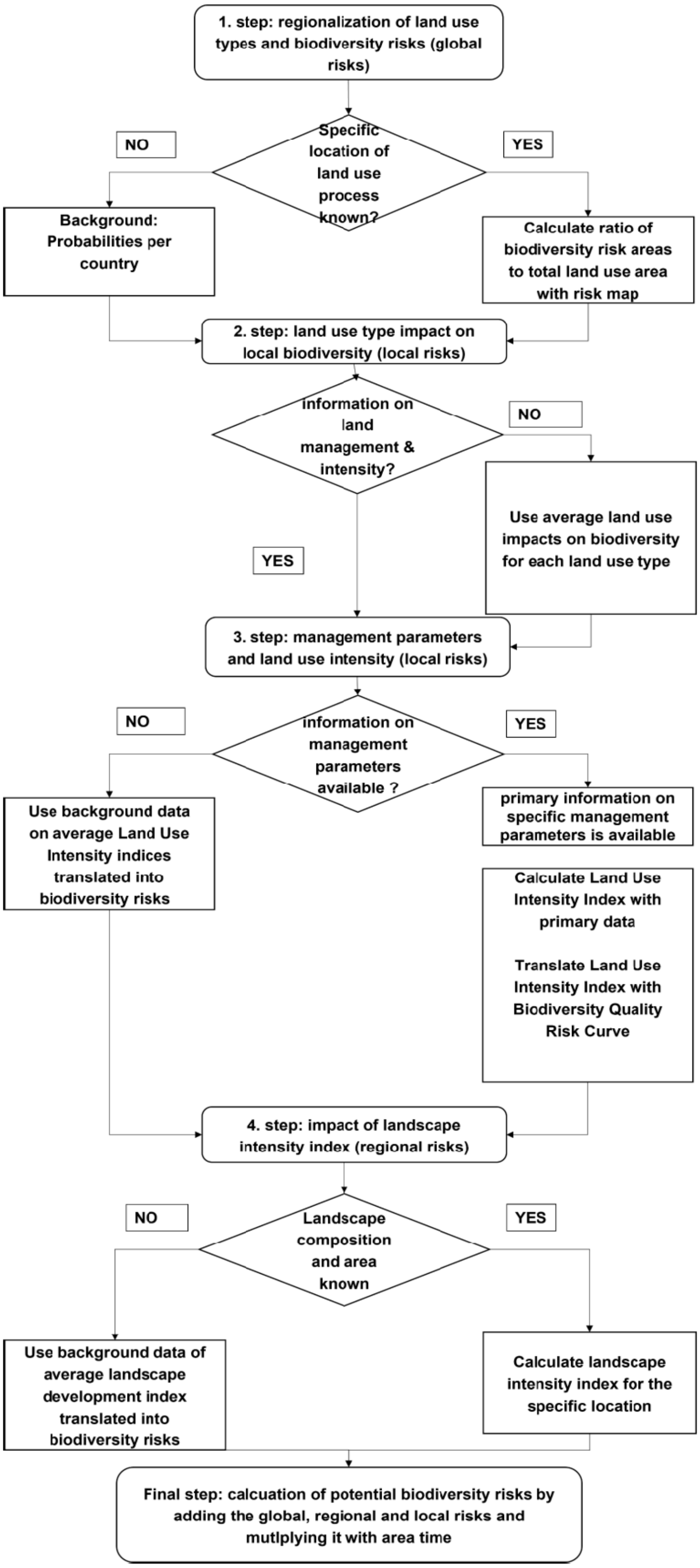

Figure 18: Decision tree for applying the BioMAPS methodology (Maier 2023)

Glossary

ADEME	French Environmental Protection Agency
AoC	Area of Concern
AoP	Area of Protection
BIA+	Biodiversity Impact Assessment+
BioMAPS	Biodiversity Multi-Scale Assessments of Product Systems
BMD	Biodiversity Monitoring Data Switzerland
BR	Biodiversity Risk
BS	Biodiversity Status
BVI	Biodiversity Value Increment
CBD	Convention on Biological Diversity
CF	Characterisation Factor
CFe	Endpoint CF
CFm	Midpoint CF
CIESIN	Center for Integrated Earth System Information
DALYs	Disability Adjusted Life Years
ECA	Equivalent Connected Area
EF	Effect Factor
ERF	Exposure Response Factor
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FF	Fate Factor
FSC	Forest Stewardship Council
GEP	Global Extinction Potential
GIS	Geo Information System
GLAM	Global Guidance on Environmental Life Cycle Impact Assessment Indicators
HC50EC50	Hazardous Concentration for 50% of the population
HF	Habitat Factor
IF	Impact Function
ILCD	International Reference Life Cycle Data System
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
LANCA	Land Use Indicator Value Calculation
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LC-IMPACT	LifeCycle Impact assessment Methods for imProved sustAinability Characterisation of Technologies
LDI	Landscape Development Index
LUI	Land Use Intensity index
MarILCA	Marine Impacts in Life Cycle Assessment
MHT	Major Habitat Type
MSA	Mean Species Abundance
PBF	Product Biodiversity Footprint
PBR	Potential Biodiversity Risk
PDF	Potentially Disappeared Fraction of Species

PEF	Product Environmental Footprint
PLA	Poly-lactic acid
PREDICTS	Projecting Responses of Ecological Diversity In Changing Terrestrial Systems
RSPO	Roundtable on Sustainable Palm Oil
RTRS	Round Table on Responsible Soy
SAR	Species-area relationship
SSD	Species Sensitivity Distribution
SSP	Shared Socioeconomic Pathway
UBR	Unified Biodiversity Risk
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP-SETAC	United Nations Environment Programme - Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative
USEtox	UNEP-SETAC toxicity model
ENEP-WCMC	United Nations Environment Programme - World Conservation Monitoring Centre
VS	Vulnerability Score
WWF	World Wide Fund For Nature
XF	Exposure Factor

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