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Comparative evaluation of life cycle impact assessment methods for biodiversity from the perspective of a car manufacturer

Master's thesis in Industrial Ecology

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Abstract

The aim of this thesis was to evaluate different life cycle impact assessment (LCIA) packages, to see how they can be used to examine a car manufacturing company's impact on biodiversity in different parts of the world, in particular related to car battery production. This was conducted through a literature study, where the first task was to identify relevant LCIA packages to be evaluated. To be examined, the package had to meet four criteria: inclusion of ecosystem quality as an area of protection, utilization of an endpoint indicator, sufficient documentation, and availability in LCA software. This resulted in the LCIA packages ReCiPe 2016, IMPACT World +, and LC-IMPACT being examined.

Once identified, the LCIA packages were evaluated by investigating their impact categories, and the research they were based on. The packages were then compared to each other to identify major differences and similarities. In addition to this, a case study was conducted on nickel sulfate, a key component in the production of nickel-manganese-cobalt batteries commonly used in electric cars, to identify major differences between the LCIA packages and to facilitate the comparison. This case study did not include LC-IMPACT, as it was not freely available in the LCA software used, OpenLCA. Also, a sensitivity analysis was performed by shifting the electricity mix, from a global, to an Indonesian and Canadian, representing two nickel-producing countries with different electricity mixes.

The results showed that IMPACT World+ and LC-IMPACT could be used for regionalized results by using regionalized characterization factors, while ReCiPe 2016 only provides global characterization factors. However, the case study revealed that finding regionalized inventory data was difficult, and without this, that advantage is lost as the packages defaults to global characterization factors.

ReCiPe 2016 and LC-IMPACT offers a clearer pathway from inventory data to endpoint than IMPACT World+, which uses a more branched approach. This leads to some inconsistency in the modeling. IMPACT World + does however offer a broader set of impact categories, 17, compared to 10 for the other two LCIA packages. Some of these extra impact categories are rather new, with new underlying research that is not as scientifically robust as some of the more established categories.

After analyzing the LCIA packages, it was clear that no single package currently offers a fully comprehensive approach to assessing biodiversity and all it entails. The packages are currently mostly focused on species diversity, overlooking other important aspects of the term biodiversity, such as genetic diversity. If a company want to fully understand their impacts on biodiversity, they cannot only depend on LCIA at its current state.

This master’s thesis was carried out in collaboration with the car manufacturer Volvo Cars, located in Gothenburg, Sweden.

Keywords: LCA, life cycle assessment, LCIA, life cycle impact assessment, biodiversity, biodiversity loss, ecosystem quality

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Sammanfattning

Syftet med uppsatsen var att utvärdera olika paket för påverkansbedömning (LCIA), för att se hur de kan användas för att undersöka en biltillverkares påverkan på biodiversitet i olika delar av världen, i synnerhet med hänsyn till produktionen av bilbatterier. Detta utfördes genom en litteraturstudie, där den första uppgiften var att identifiera relevanta LCIA-paket för utvärdering. För att bli utvärderad krävdes det att paketen uppfyllde fyra kriterier: inkludering av ekosystemkvalitet som ett skyddsområde, användning av slutpunktsindikatorer, tillräcklig dokumentation, samt att vara tillgänglig i LCA-program. Detta resulterade i att LCIA-paketen ReCiPe 2016, IMPACT World+ och LC-IMPACT blev utvalda och utvärderade.

Efter att ha blivit identifierade blev LCIA-paketen utvärderade genom att undersöka deras påverkankategorier, samt forskningen de var baserade på. De jämfördes sedan med varandra för att identifiera större skillnader och likheter. Utöver detta utfördes en fallstudie på nickelsulfat, vilket är en viktig komponent i produktionen av nickel-mangan-kobolt-batterier som är vanligt förekommande i elektriska bilar, i syfte att kunna identifiera skillnader mellan LCIA-paketen, och för att underlätta jämförelsen. Denna fallstudie inkluderade inte LC-IMPACT eftersom den inte kunde användas gratis i OpenLCA som var den programvara som användes. En känslighetsanalys utfördes också genom att ändra elektricitetsmixen, från en global, till en indonesisk och kanadensisk, vilka representerar två nickel-producerande länder med olika elektricitetsmixar.

Resultaten visade att IMPACT World+ och LC-IMPACT kunde användas för regionaliserade resultat genom att använda regionaliserade karaktäriseringsfaktorer, medan ReCiPe 2016 endast tillhandahåller globala karaktäriseringsfaktorer. Fallstudien visade dock att det var svårt att hitta regionaliserade inventeringsdata, och utan detta förloras fördelen med regionalisering eftersom paketen då använder globala karakteriseringsfaktorer, precis som ReCiPe 2016.

ReCiPe 2016 och LC-IMPACT har en tydligare väg från inventeringsdata till slutpunkt än IMPACT World+, som använder ett mer förgrenat tillvägagångsätt. Detta leder till en viss inkonsekvens i modelleringen. IMPACT World+ erbjuder dock en bredare uppsättning påverkanskategorier, 17 jämfört med 10 för de två andra LCIA paketen. Några av dessa extra påverkanskategorier är ganska nya, med ny underliggande forskning som inte är lika vetenskapligt robust som för några av de mer etablera kategorierna.

Efter att ha analyserat LCIA paketen stod det klart att inget enskilt paket för närvarande erbjuder ett heltäckande tillvägagångssätt för att bedöma biologisk mångfald och allt det inkluderar. LCIA paketen är för närvarande mest inriktade på mångfald av arter och förbiser andra viktiga aspekter av själva begreppet biologisk mångfald, såsom genetisk mångfald. Om ett företag vill få fullständig förståelse för sin påverkan på den biologiska mångfalden kan de inte endast förlita sig på LCIA i dess nuvarande form.

Den här masteruppsatsen gjordes i samarbete med Volvo Cars, Göteborg, Sverige.

Nyckelord: LCA, livscykelanalys, LCIA, påverkansbedömning, biologisk mångfald, förlust av biologisk mångfald, ekosystemkvalitet

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Klara Larsson and Sara Sjögren, June 2025.

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1 Introduction

Biodiversity can be defined as the variety and variability of life on Earth, and is often quantified in terms of species richness, which represents the number of different species within a given area (Pimm, 2025). Maintaining a high biodiversity is of high importance to humanity since it provides us with many benefits such as pollination, food, water purification and soil fertility (Shaw, 2024). Scientists have seen a strong correlation between disease outbreaks and loss of biodiversity, especially diseases transferring from animals to humans. Moreover, biodiversity can help combat climate change by maintaining a stable ecosystem that can act as carbon sinks. Forests and wetlands can also help to withstand the consequences of climate change, such as torrential rain. Beyond its environmental and health benefits, biodiversity is also essential for economic stability. Many industries, including agriculture, fisheries, and tourism, depend directly on thriving ecosystems. Many people, especially in developing countries, also rely on nature for their personal livelihood. The natural resources can both provide them with food and natural medicine, as well as an income. According to the WHO (2020), biodiversity is experiencing a rapid decline, with extinction rates currently estimated to be 10 to 100 times higher than the natural background rate. Climate change, deforestation and destruction of habitat are some factors mentioned as contributors to this. IPBES (2019) points out that achieving the Sustainable Development Goals depends on healthy ecosystems and biodiversity. Importantly, this does not only include nature related goals, but also goals related to education, peace, economy and equality.

Traditionally, many companies have focused their environmental reporting on climate change, and in particular CO_2 emissions (Kronschnabl et al., 2024). However, in recent years, companies have been seen to expand their nature-related reporting to include more aspects than just climate change. Among these aspects, biodiversity was the category that increased the most. In line with this broader shift observed worldwide, the company Volvo Cars has shown growing interest in understanding and managing its impact on biodiversity.

Volvo Cars is Sweden's leading automotive manufacturer and is on a journey away from internal combustion to electric cars (Volvo Cars, 2023). The company has set a target for 90-100% of its global sales volume to be comprised of electric and plug-in hybrid vehicles by the year 2030. Long term, they are aiming for full electrification of their car fleet as a part of their strategy to reach net zero greenhouse gas emissions by 2040.

The global electric vehicle market is projected to grow rapidly in the coming decades (IEA, 2022a). Although transitioning from internal combustion to electric cars will reduce the demand for fossil fuel, it is anticipated that the demand of raw material needed in the batteries, including metals such as lithium and nickel, will increase by a factor of 40 by 2040 (IEA, 2022a). While this shift constitutes as a response to climate change, it is important to recognize that other environmental factors must also be considered the in the broader context of sustainability.

A common way to assess the environmental impacts of products is to use life cycle assessment (LCA) (Baumann & Tillman, 2004). LCA is a standardized framework that assesses the potential environmental impact of a product through its entire life cycle, from extraction of raw material to disposal (ISO, 2006). The framework consists of goal and scope definition, inventory analysis, impact assessment and interpretation (Baumann & Tillman, 2004). The life cycle impact assessment (LCIA) phase plays a crucial role in linking the inventory data to environmental impacts by grouping the emissions and resources into impact categories and quantifying their effect through characterization models. These impact categories are linked to broader areas of protection, which typically include the natural environment, human health, and resources. In the context of biodiversity-focused assessments, the area of protection most relevant is the natural environment, and is often measured by species extinction (Callesen, 2016). These concepts can however not be fully equated, as species loss is only one measurement of biodiversity, and protection of the natural environment includes both the function and structure of ecosystems (Callesen, 2016; European Commission, 2010). Natural ecosystems are complex, with multiple interactions at different levels, making them challenging to assess and translate into common metrics. This is, however, the purpose of the LCIA. Importantly, LCIA is not a single standardized method, but rather a framework within which multiple methods have been developed (Sanyé-Mengual et al., 2023). As a result, applying different LCIA methods to the same inventory data can yield varying results.

1.1 Aim

Against this background, this thesis will explore how some different LCIA packages are constructed, focusing on the natural environment and biodiversity, from the perspective of a car manufacturer.

The aims of this study are the following:

- To compare the underlying midpoint indicators that lead up to the endpoint indicators for ecosystem quality.
- To compare methods for transformation of midpoint indicators to the endpoint indicator for ecosystem quality.
- To evaluate the relevance of different endpoint indicators for ecosystem quality for a car manufacturing company, considering both biodiversity impact representation and feasibility for the company, through a case study.

To achieve this, the study analyzes existing LCIA packages. The LCIA packages were chosen during the initial literature study. The identified LCIA packages were then compared and evaluated, with regards to both midpoint and endpoint impact categories.

To further examine the practical implications of the LCIA packages, a case study about nickel, a key material in battery production for electric cars, was performed. The purpose of this case study was to evaluate whether the selected LCIA packages are feasible in practice, and to investigate why potential differences in the results occur.

2 Background

The following section provides background information on key concepts relevant to the thesis, including LCA, biodiversity, ethics, sustainable development and nickel connected to car batteries.

2.1 Life cycle assessment

Originally, the demand for monitoring environmental pollution, energy and material scarcity connected to products was the reason for the development of life cycle-oriented approaches (Hauschild et al., 2018). LCA methodologies and applications have since the 1960s experienced a strong progress. The methodology has been developed over many years, and it was during the 1980s that the need for commonly agreed-upon principles was widely realized. The discussion about the methodology led to the implementation of a standardization process and finally to the ISO 14040 standard in 1997, which is since considered a baseline for LCA. The standard is, among others, part of the Environmental Footprint (EF) initiatives from the EU Commission (European Commission., n.d.).

LCA can be defined as follows (Hauschild et al., 2018):

"a tool to assess the potential environmental impacts and resources used throughout a product's life cycle i.e. from raw material acquisition, via production and use stages, to waste management".

The results can then be used to target the "environmental hotspots" of different life stages, with different management measures (Baumann & Tillman, 2004). The standard LCA methodology, illustrated in Figure 1, consists of a goal and scope definition, an inventory analysis, an impact assessment and an interpretation.

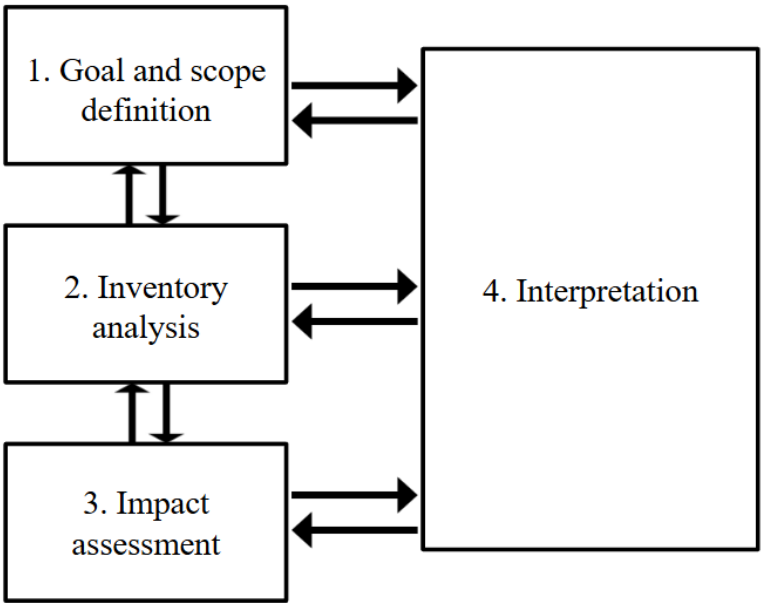

Figure 1. Illustration of the LCA framework. Author's own figure, based on a similar figure in Baumann & Tillman (2004).

Goal and scope

The goal and scope definition is the first part of an LCA and includes deciding the purpose and which product to study (Baumann & Tillman, 2004). Stating the intended application of the study, the reason behind it and to whom the results are aimed to be communicated are essential according to the ISO 14040 standard. The goal and scope should be consistent with the intended application and clearly defined. This is done through specifying the problem formulation, defining the context and boundaries, as well as the functional unit. LCA relates environmental impact to the function of a product system, which is why there is a need to express the function, in terms of a quantified functional unit. The boundaries set are called system boundaries, which include geographical and temporal boundaries, as well as the boundary between the natural and technical system.

Inventory analysis

The life cycle inventory analysis (LCI) aims to build a systems model according to the goal and scope definition (Baumann & Tillman, 2004). This model is organized as a flow model of a technical system with specific system boundaries, often “cradle to grave” or “cradle to gate”. The cradle to grave refers to the whole life cycle being modeled while cradle to gate covers the part from resource extraction to manufactured product (Baumann & Arvidsson, 2015). The environmentally relevant flows are considered, mainly the use of scarce resources and emissions of harmful substances (Baumann & Tillman, 2004). The system studied is often visualized as a flowchart that shows the activities included, such as production, processes, transports, use and waste management. The flows between activities are also included in the flowchart, and the values for the processes and transports are obtained. The input and output data can include raw materials, energy carriers, products, and solid waste. The last step in the inventory analysis is the calculation of the inventory results, i.e, resource use and pollutant emissions in relation to the functional unit. An important aspect to consider during an LCI is if the technical processes produce more than one product, in which case the emissions or resources need to be allocated, i.e. partitioned, between its different products. There is also a possibility to avoid allocation through including other necessary products or processes to make sure the studied systems obtain equal functionalities, known as system expansion (Baumann & Arvidsson, 2015).

Impact assessment

The LCIA is a continuation of the LCI by calculating the impacts of the inventory results (Baumann & Tillman, 2004). The purpose of the LCIA is thus to turn the inventory results into more relevant information for the environment. To be able to do this, there are a few steps to follow. The first step is the *classification* of the inventory parameters by sorting them according to the type of environmental impact category they contribute to, for example global warming, acidification and eutrophication. The next step is the *characterization*, where the amount of emissions or resource extraction contributing are calculated per impact category, depending on the category they belong to. The calculations required for this are based on models of cause-effect chains in the natural systems, which can sometimes be simplified. The calculated impact categories may in some cases require to be interpreted or aggregated even further. This can be done through *weighting,* which is not recommended for publicly disclosed LCA studies according to the ISO standard 14040 (2006), but can sometimes be used in other contexts. Individual values and preferences are frequently used as a basis for a weighting system.

During the characterization step, the different environmental impact scores are calculated through characterization factors (CFs) (Huijbregts et al., 2017a). They indicate the environmental impact per unit of stressor, e.g. per kg of emission released or resource extracted. The CFs are often derived in two different ways, at midpoint level or at endpoint level. According to Huijbregts et al. (2017a), the CFs at midpoint level are located somewhere along the cause-impact pathway, while at the endpoint level they reflect the damage to the areas of protection, as shown in Figure 2. These areas of protection are human health, resource scarcity and ecosystem quality, which are easier to interpret in terms of relevance of the environmental flows. The midpoint characterization, on the other hand, has a stronger relation to the environmental flows and comes with lower uncertainty. As shown in Figure 2, there exist ready-made LCIA packages that can be applied. They consist of impact pathways for midpoint and/or endpoint with pre-calculated CFs, and one example is the ReCiPe 2016 package.

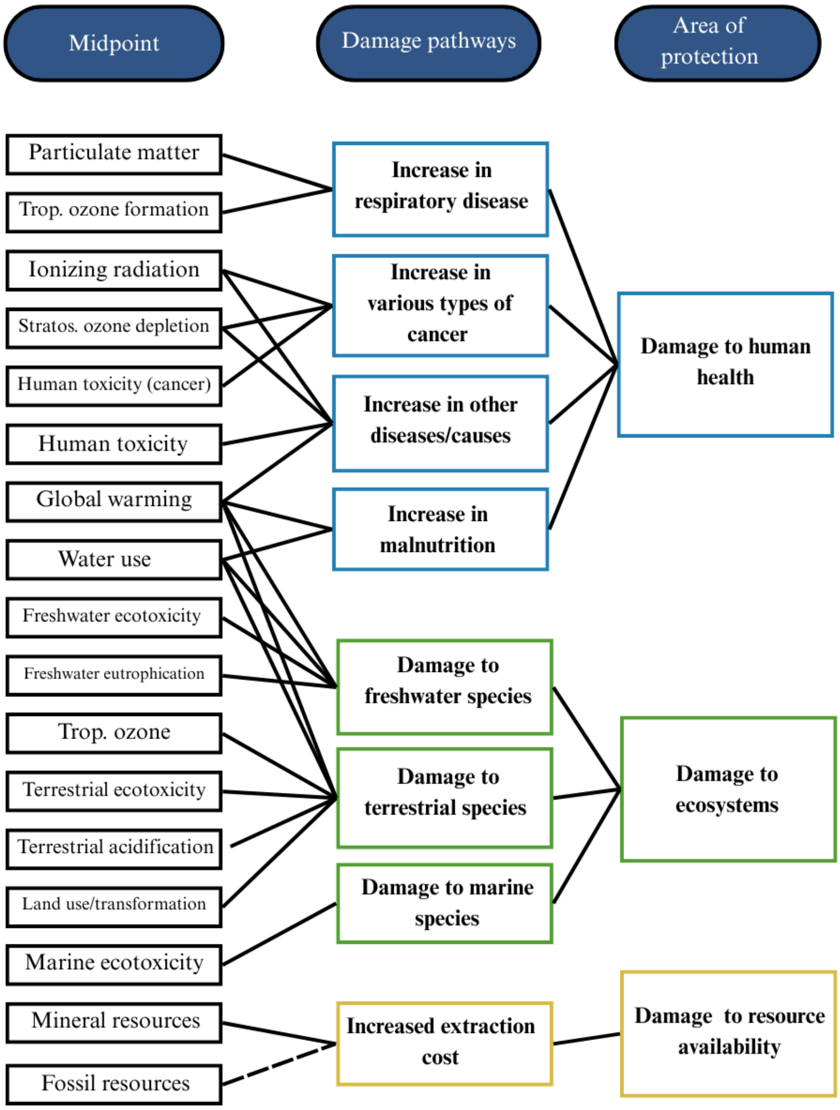

Figure 2. Overview of the impact categories covered in the ReCiPe 2016 methodology and their relation to the areas of protection. Image modified from Huijbregts et al. (2017a), licensed under CC BY 4.0.

Interpretation of results

The final step of an LCA is the interpretation of the results, where the results are analyzed in order to draw conclusions (Baumann & Tillman, 2004). According to the ISO 14040 standard, the interpretation is "a phase of LCA in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations". The structure of the interpretation phase can be described in two different parts, where one is the identification of significant issues, e.g. critical methodological choices and important environmental findings. The other is to establish confidence in the findings through checking the completeness, consistency and uncertainty. These together act as a basis for the final conclusions and recommendations of the whole study. There are different ways to present qualitative and quantitative results. Often, LCA results are presented in bar diagrams.

A contribution analysis can be used to get a better understanding of the LCIA results (Baumann & Tillman, 2004). This analysis identifies which environmental loads contribute most to the total environmental impact, but also identifies the relatively unproblematic emissions that have a lower contribution. A sensitivity analysis on the other hand can be used to identify the most crucial inventory or impact assessment data, or the significance of alternative methodological choices such as changes in allocation. All LCA studies require a large amount of gathered information and data, which makes it important to test the robustness of the results, through changes in critical and estimated data. To perform a sensitivity analysis, one systematically changes the input parameters and observes where a small change leads to a reversal in the results.

2.2 Biodiversity and biodiversity loss

According to the Convention on Biological Diversity (UNEP, 1992), article 2, biodiversity can be defined as:

"*The variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems.*"

From this definition, three different kinds of biodiversity can be identified, as explained by Cunningham & Cunningham (2008):

1. **Genetic diversity**: The variety of different genes within one species.
2. **Species diversity**: The variety and quantity of organisms found within particular communities or ecosystems. It consists of two main elements: *species richness*, which counts the total number of species present in an ecosystem, and *species evenness*, which looks at how balanced the population sizes of the species are. I.e. if there is roughly the same number of individuals within each species.
3. **Ecological diversity**: The variety, richness and complexity of a biological community.

An illustration of the this can be seen in Figure 3.

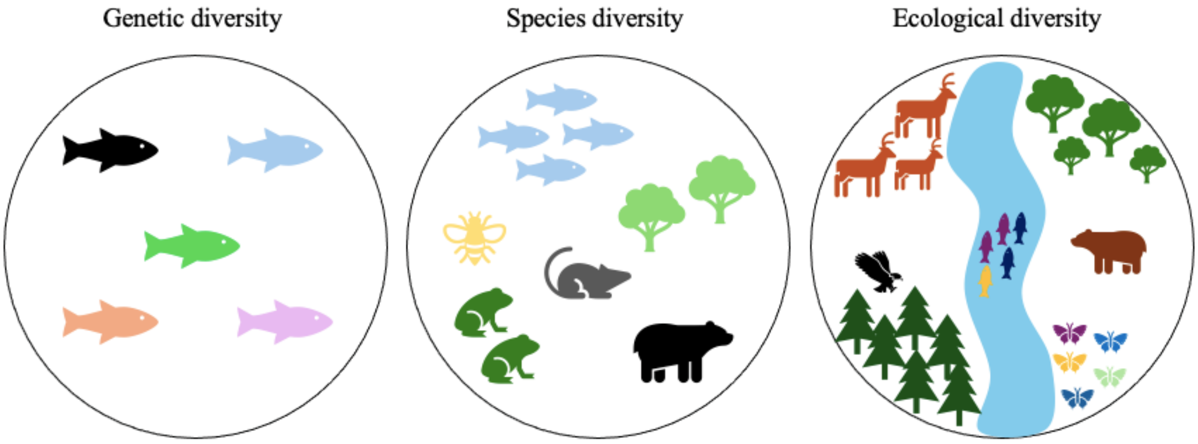

Figure 3. Illustration of the different kinds of biodiversity.

While the Convention on Biological Diversity states some different ways to think about biodiversity, it is common to primarily link the term to species richness (Rafferty, 2024). As a result, biodiversity loss is often equated with the decline of species within an ecosystem. However, only focusing on species lost can overlook other important aspects that can affect the long-term status of the ecosystem. A fast decline in population size can decrease the possibility of finding a suitable partner for reproduction, as well as increase the possibility of inbreeding. Both of these can further reduce biodiversity.

There are two types of biodiversity loss: natural and human driven (Rafferty, 2024). Natural biodiversity loss occurs due to factors out of human control. Seasonal changes can both increase and decrease biodiversity, with plants being more prone to grow and thrive during water periods, which in turn herbivores can utilize as food. Other disturbances can include natural environmental disruptions such as wildfires and floods. These are temporary disturbances that ecosystems often can adapt to. In contrast, human driven biodiversity loss tends to be more long-lasting. Drivers of this include habitat loss, invasive species, overexploitation, pollution and climate change. Recent studies have shown that land use changes are the main driver of biodiversity loss (Jaureguiberry et al., 2022).

The ecosystems are also greatly affected by the variety of species that inhabit them (Ellison, 2019). There are different kinds of important species living in an ecosystem, one of which is the foundation species. They determine the regional and local biodiversity, control the ecosystem dynamics as well as having intrinsic value to the people who live near or with them. Foundation species are also abundant and common, which is why they have received less attention from environmental professionals, who focus more on threatened and endangered species. Another important species in an ecosystem is the keystone species, which is made up of either predators or herbivores and increases the species richness by feeding on dominant competitors. The keystone species is often limited in number, unlike the foundation species.

2.3 Ethics

When talking about ethics with regards to sustainable development, a common distinction is who or what hold moral status (Hedenus et al., 2022). In anthropocentrism, humans are granted a special role as the most important beings, separated from nature (Boslaugh, n.d.). In this view, human needs and well-being are considered to have intrinsic value, meaning they are valued in and of themselves, while all other entities, including animals and nature, have instrumental value, meaning they are valued only for the roles they play in supporting human life, providing resources, or serving human interests (Hedenus et al., 2022). This does not imply that nature lacks significance, but it is not valued in itself. In other word, nature's resources such as food, timber and ecosystem services, are considered important solely because they serve human needs and interests. In sustainable development, anthropocentrism also includes future generations of humans, meaning we should take into consideration the need of future generations.

An extension of anthropocentrism is zoocentrism (Hedenus et al., 2022). In this view, sentient beings are also granted moral status. This does not necessarily mean that animals should have the exact same standings as humans, but they should be considered when making decisions that could affect them. A further expansion of this is biocentrism. The moral standing here is given to all life, including humans, sentient beings as well as non-sentient beings such as plants. In this viewpoint, it is argued that all life has a goal of living, thriving and procreating, which should be valued regardless of one's ability to express these desires.

In contrast from the previous ethical frameworks, ecocentrism shifts the focus from individual beings to collective systems and the broader whole (Hedenus et al., 2022). In this view, ecosystems hold moral value. While individuals are not in focus anymore, this does not mean that humans cannot utilize natural resources. The problem will arise if the use would threaten the stability of the ecosystem, such as extensive hunting. But hunting to a certain limit could even be viewed as positive from an ecocentric point of view, since this could maintain the balance of species distribution, or control the population of invasive species which threaten the balance of the ecosystem.

Anthropocentrism and ecocentrism and be seen as opposing perspectives, with individual viewpoints varying along a spectrum between the two (Hedenus et al., 2022). In the context of sustainable development, efforts are often rooted in an anthropocentric approach, where ecosystems are primarily seen as an instrumental value to human society. It can therefore be argued that we should protect nature, but rather for the many resources it provides humans than for itself. A visualization of the ethical frameworks can be seen in Figure 4.

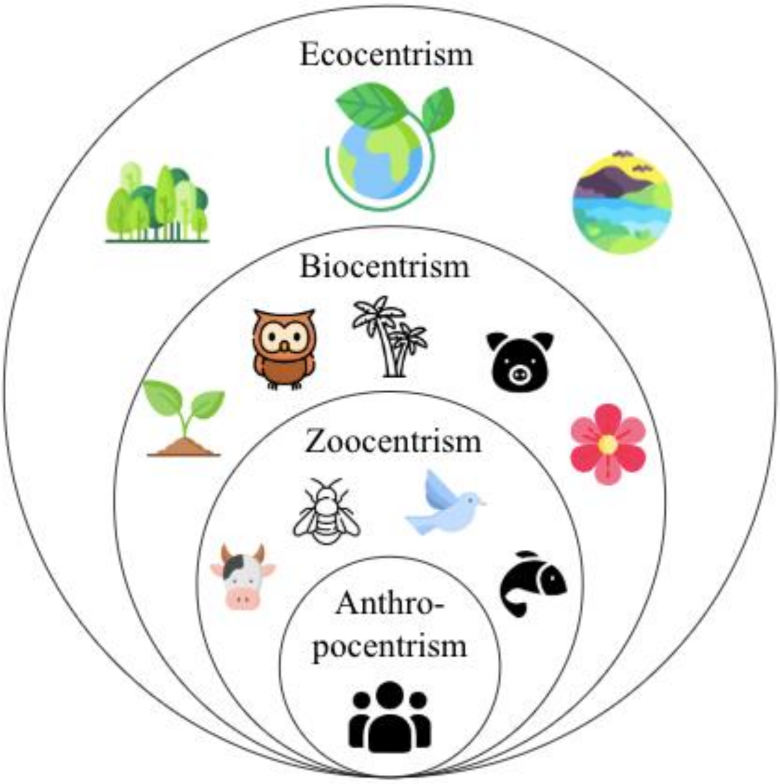

Figure 4. Illustration of the environmental ethical frameworks. Author's own figure, created from the conceptual framework from Hedenus et al. 2022.

2.4 Sustainable development

According to the report Our Common Future (World Commission on Environment and Development, 1987), also known as the Brundtland report, sustainable development can be defined as follows:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

In an attempt to clarify what is meant by human needs in this case, the concept has been divided into three dimensions; ecological, economic and social (Hedenus et al., 2022). The *ecological dimension* concerns the sustaining of ecosystems and their ability to provide humans with natural resources. It is usually divided into two parts, the first being environmental production capacity. This is nature's capability of providing natural resources, such as clean water, fuel and food for us humans, but also ecosystem services such as nutrient circulation, pollination as well as cultural and aesthetic values. The second part is the environmental assimilative capacity, which involves nature's ability to take care of pollutants and other environmental impacts, such as absorption of carbon dioxide.

The *economic dimension* focuses on the allocation and utilization of resources (Hedenus et al., 2022). This dimension is also divided into two parts, the first being finite natural resources. These are substances found in Earth's crust that are not renewable, such as fossil fuels and metals. The second part is human-made capital. This includes both physical capital i.e. buildings, and human capital, i.e. human knowledge. Finding a balance in managing these resources, both for the current generation and future generations, is essential to ensuring long-term sustainability.

The social dimension has traditionally been less frequently discussed in the literature than the previous two, and exactly what is contains has also been up for debate (Hedenus et al., 2022). The core of the social dimension focuses on creating fair and inclusive societies where all individuals have access to basic human rights, essential services, and opportunities for well-being. However, Hedenus et al. (2022) argues that these are rather means of sustainable development, and to reach these horizontal and vertical social relationships are needed. Horizontal relations refer to networks between people and organizations, which will lead to better cooperation, trust and ultimately solutions that benefit many people. Vertical relations refer to formal institutions, such as legal systems and bureaucracies.

The distinction between these three dimensions is not always clear, as they often intertwine (Hedenus et al., 2022). For example, fair utilization of a resource often requires collaboration. The dimensions may occasionally also come into conflict with each other, e.g. building a dam for energy can increase the human made capital in the economic dimension, but at the same time destroy the natural habitat for some species. This highlights the need to take a holistic approach, considering various factors and potential impacts when making decisions about sustainable development, so that no dimension is neglected. An illustration of the concept of sustainable development and its three dimensions can be seen in Figure 5.

While sustainability is often discussed in terms of all three dimensions, this study emphasizes the environmental aspect by assessing biodiversity indicators within LCA. However, biodiversity can have indirect impacts on both the economic and social dimension. Biodiversity help sustain health ecosystems, supports industries like fisheries and forestry, and contributes to social and cultural well-being. This makes biodiversity and biodiversity loss an interesting issue in all three dimensions of sustainable development.

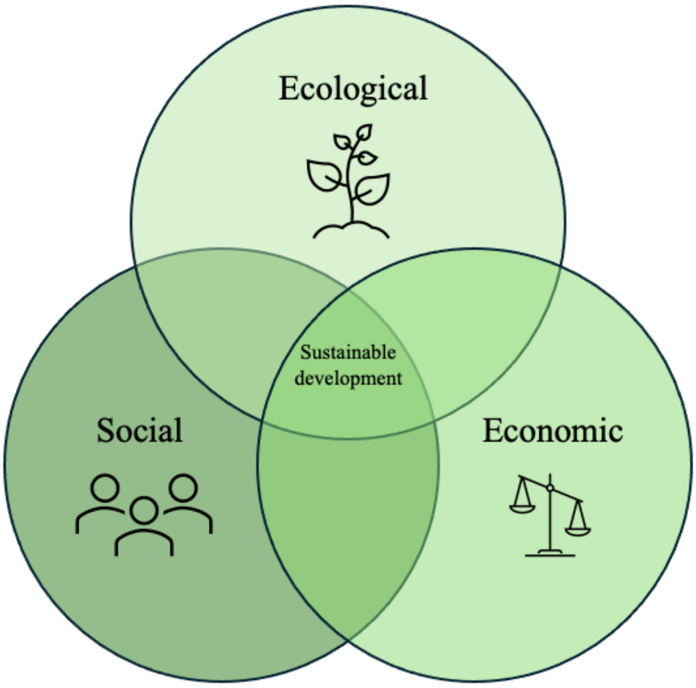

Figure 5. The three dimensions of sustainable development. Author's own figure, based on a similar figure in Hedenus et al. 2022.

2.5 Car batteries and nickel

The battery in hybrid and electric vehicles (EVs) determines both the power reserve of the car and the operation period, which makes it an important component (Grebtsov et al., 2024). There are different kinds of car batteries on the market, but the market for rechargeable batteries is dominated by the lithium-ion batteries. A lithium-ion battery consists of an anode and a cathode separated by a porous material impregnated with electrolytes, through which lithium ions can flow (U.S. Department of Energy, 2023). The cathode, which is the positive electrode, is often made of lithium oxides. The anode, or the negative electrode, is usually made of graphite. During charging, lithium ions are stored in the anode, as electrons are forced to flow from the cathode to the anode by an external power source, thereby charging energy.

The nickel-manganese-cobalt oxide (NMC) battery is a type of lithium-ion battery, where the material in the cathode consists of a NMC (Evro et al., 2024). The combination of metals gives a high energy density, which makes the NMC battery suitable for high-power EVs with high energy storage capacity. It is also suitable for applications where minimizing weight is important but a high energy output from the battery is still required. Initially, the NMC cathodes contained nearly the same amount of nickel, manganese and cobalt, but in recent years, manufacturers have increased the proportion of nickel in efforts to increase the energy density (McRae, 2024). This has led to a reduction in the reliance on cobalt because of the decreasing need of the material in the batteries. Nickel is thus an important metal for battery production and an important metal for the car manufacturers.

The countries with the biggest production of nickel in 2024 were Indonesia, the Philippines, Russia, Canada, China and Australia (U.S. Geological Survey, 2025). In 2024, the estimated global mine production of nickel decreased but the production in Indonesia still increased by 8%. Globally, nickel reserves have been estimated to contain more than 350 million ton of nickel with the biggest shares in magmatic sulfide deposits and laterites. Nickel ores are generally mined from sulfide or laterite ore bodies, where the laterite ores with a nickel concentration of 1-2.7% are mostly mined through open-pit (Wei et al., 2020). The sulfide ores are mined through both underground methods and open-pit, and have a concentration of 1-3% nickel. The refining of the laterite and the sulfide ores to nickel sulfate is done through hydrometallurgical processes, such as leaching with sulfuric acid, chlorine or ammonia, which often produces cobalt or other metals as co-products.

Refined nickel products have different quality and are generally divided into Class I which is high-purity nickel metal and Class II which contains lower levels of nickel, with a number of intermediates used in different process routes (Tijsseling et al., 2023). Class I and II products along with intermediates can in turn be converted to nickel sulfate hexahydrate, which is the product used in the battery industry. 1 kg of nickel sulfate hexahydrate, from here referred to as only nickel sulfate, has a nickel content of 22%. According to Sphera (2020), the metallurgical processes, such as smelting and leaching, are the major contributors to the environmental impacts. However, the sources of emissions differ depending on the ore processed and the technology used. Sulphur dioxide is for example an emission connected to the processing of the sulfidic ore, which contributes to a high proportion of the acidification impact. The nickel smelting is an energy intensive process, where the required energy for producing one ton of nickel metal (100% Ni) from nickel ore is 174 GJ and the associated global warming impact is 14 t CO_2-eq (Wei et al., 2020).

The total energy consumption and carbon emissions are highly dependent on the kind of electricity used, such as coal or hydropower.

The transformation of Indonesia’s way of mining has occurred rapidly (Lakshmi & Hodgson, 2025). The turnaround from being a country who barely used its nickel reserves to being the world’s biggest supplier has happened in a decade. Indonesia also holds the world’s largest reserves of the metal with about 55 million tonnes as of 2024 (U.S. Geological Survey, 2025). The dramatic growth and the economic take-off have not only led to celebration and price reductions, but also concerns. Indonesian nickel has been criticized for being “dirty” due to use of energy from coal-fired plants and the deforestation associated with the production (Lakshmi & Hodgson, 2025). The environmental impacts from a mining site are considerable, including everything from air pollution to forest loss and land transformation due to the mining process. This can in turn affect living organisms in and around an area, which in worst case leads to a loss of biodiversity (Worlanyo & Jiangfeng, 2021).

The global nickel demand is projected to continue to rise in order to support renewable energy production and low-carbon technologies, such as EVs (Luckeneder et al., 2024). A related problem is that it is only recently that studies have started to systematically assess the extent to which nickel mining contributes to deforestation and biodiversity loss. The EU is a major consumer of nickel and has contributed to a forest loss of 6.7 km^2 in Indonesia, 3.5 km^2 in Canada and 2.9 km^2 in Australia from 2001 to 2019 (Luckeneder et al., 2024).

3 Method

The following sections outlines the methodology of the study. This includes the literature study, personal meetings, evaluation of the LCIA packages as well as a case study. The available literature about LCIA frameworks often use the word “method” to describe both the overall framework, as well as the underlying impact categories. To distinguish these in this study, it was decided to use the term “LCIA packages” to refer to full sets of impact categories and models under a specific framework, while the term “method” is used to describe the individual impact categories within each package. This distinction was made to improve clarity and consistency throughout the report.

3.1 Literature study

As a first step of the project, a literature search was performed. Relevant literature was mainly found through the databases Google Scholar, ScienceDirect, Google and Chalmers Library. Scientific reports, books, official government websites and official organization reports were primarily used. Keywords used in the literature search included biodiversity, LCA, LCIA and LCIA method.

The literature study provided a basis for selecting which LCIA packages to examine. Due to time limitations, not all existing LCIA packages could be evaluated. Since the car company is currently using ReCiPe 2016, it was decided from the start that this would be one of the LCIA packages evaluated. The other LCIA packages evaluated were selected during the literature study. To be included in the final analysis, each method must receive a “yes” to all the questions below:

- Does the LCIA package include ecosystem quality as an area of protection?
- Does the LCIA package apply endpoints?
- Does the LCIA package have sufficient documentation for a thorough review?
- Is the LCIA package available to use in LCA software programs?

This process is illustrated in Figure 6.

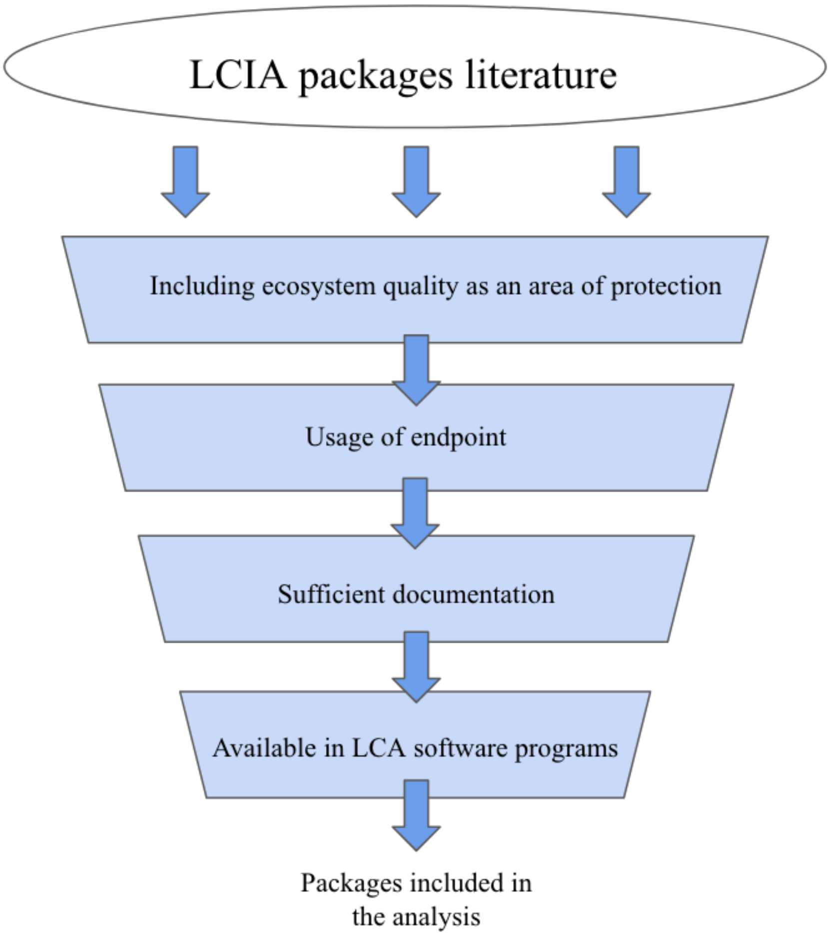

Figure 6. Illustration of the process of selecting LCIA packages to be evaluated.

The packages included in the analysis were ultimately ReCiPe 2016, IMPACT World+ and LC-IMPACT. These are further discussed and analyzed in Section 4. A shorter discussion about the package GLAM can also be found in the result section.

3.2 Personal meetings

Several personal meetings were held with several people at the car company. Initially, introductory meetings were arranged to take place with our supervisor, and other people involved in the project, providing an opportunity for both parties to exchange information and ask questions. Personal meetings with other relevant people at the company were set up by the supervisor. This was done to get a bigger picture and to hear firsthand what is important to the company and different departments.

Before each meeting, some interview questions were prepared, with the questions being tailored to each interviewee. Since every employee had a different role and area of expertise, no standardized set of questions was used. Nevertheless, the interviews were conducted in an informal way, with new questions arising as the meeting continued.

The purpose of the personal meetings with the supervisor and related people was to track the progress and make sure the scope of the master thesis project aligned with the intentions of the company. The purpose of the meetings with other relevant people was to get an understanding of how the company operates.

3.3 Comparison of the LCIA packages

After identifying the relevant LCIA packages, a comparison was performed. Firstly, the LCIA packages and included impact categories were put in a table, together with the midpoint unit, endpoint unit as well as the underlying sources on which the impact category was based. The table was then color coded to facilitate a comparison. Green color indicates that the impact category is based on the same sources as the other LCIA packages. Blue color indicates that the impact category is only used in one package and not the other. Finally, red color indicates that the underlying sources of a specific impact in a package is based on different sources than the other LCIA packages.

The LCIA packages were also compared using the following questions:
- Is the package available for use in LCA software?
- How many impact categories does the LCIA package include?
- Is the LCIA package regionalized? Meaning that it provides specific CFs for specific regions.

3.4 Case study

To explore how different LCIA packages capture and quantify different impacts, a case study was conducted on the production of nickel sulfate. Due to its widespread utilization in car batteries, nickel was selected as the focus of the case study in consultation with the car company. The assessment was carried out using the LCA software OpenLCA (v.2.4.0.), together with the database ecoinvent 3.11. The decision to use OpenLCA was based on several factors. It is free of charge and is recognized as the most extensively used LCA software across the world (GreenDelta, n.d.). The ecoinvent database was selected due to its extensive coverage, high level of transparency, and strong reputation within the LCA community (Ecochain, 2021).

The dataset used for the case study was “market for nickel sulfate | nickel sulfate | Cutoff, U – GLO”, which represents a global average of nickel sulfate production, from the cradle to the gate, including transportation. This served as the baseline scenario in the analysis. Efforts were made to find a region-specific dataset, but no such dataset was found. During the review of the available dataset, it was also determined that adapting all data to represent a certain country or region would be too time-consuming given the volume and complexity of the data. In addition, since the dataset represented a global average, it was also difficult to know if the amount used of each input would differ for specific sites.

During the literature review, three LCIA packages were identified. Two of the LCIA packages, ReCiPe 2016 and IMPACT World+, were applied in the case study to enable a comparison of their results and modeling approaches. Both LCIA packages are freely available in OpenLCA, whereas the third package, LC-IMPACT, requires a paid license. Therefore, this LCIA package was not included in the case study. For the comparison between the two LCIA packages to be as relevant as possible, it was decided that both would be evaluated with a 100-year time perspective. In ReCiPe 2016, this corresponds to the “hierarchist perspective”, and for IMPACT World+, this corresponds to a “shorter term-perspective” (Bulle et al., 2019b; Huijbregts et al., 2017a)

The two LCIA packages in the case study do not use the same unit. It was therefore not possible to perform a direct numerical comparison between them. Instead, it was decided to perform a contribution analysis by identifying the main contributors to ecosystem quality impact with each package. This was done by turning the results into a 100% stacked bar chart, where the impact results were normalized to reveal the percentual contribution to the total endpoint score. This allowed for a direct numerical comparison between the two LCIA packages, and highlighted similarities and differences between the relative contributions of each midpoint impact category.

Lastly, a sensitivity analysis was conducted. After studying the datasets, it was decided that the sensitivity analysis would focus on the electricity mix. Electricity was a key input in the dataset, and a lot of datasets of electricity mixes from different countries were available in ecoinvent. It was decided that the two nickel-producing countries Indonesia and Canada would be used as contrasting case studies. Indonesia has a large share of non-renewable sources, such as coal, in their electricity mix (IEA, 2022b). In contrast, Canada’s electricity mix is dominated by hydro and nuclear power (IEA, 2023). Using the electricity mix of these two nickel-producing countries provided a useful comparison between carbon-intensive and low-carbon energy in the sensitivity analysis. The exact changes made to the original dataset can be found in the Appendix.

4 Results

After the initial literature study, three LCIA packages were identified that fulfilled all the criteria in Section 3.1 and were therefore selected to be evaluated in detail. These were ReCiPe 2016, IMPACT World+ and LC-IMPACT. In this section, a detailed presentation of these three LCIA packages, their impact categories related to ecosystem quality, and the underlying methods and equations is provided. In addition, a brief presentation of GLAM is also made. GLAM was deemed an interesting LCIA package due to it being an initiative from the United Nations but lacked some elements that prevented it from being studied in detail in this thesis. At the end of the section, a summary of the three LCIA packages studied are presented as well as the package comparison and case study.

4.1 GLAM

The global guidance for life cycle assessment indicators and methods, shortened GLAM, is an initiative from the United Nations Environment Programme's (UNEP's) Life Cycle Initiative, aimed at developing a new LCIA package (UNEP, n.d.-a). The work started in 2013, with the goal to "establish a comprehensive, consistent and global Environmental Life Cycle Impact Assessment Methods, covering classification, characterization, normalization and weighting to assess the life-cycle impacts of products and services on human health, ecosystem quality and natural resources" (UNEP, n.d.-a).

While this LCIA package has been deemed interesting, it has some challenges that make a deeper analysis difficult. Firstly, the available documentation is contradictory and inconsistent. They have published two reports: Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1 and Volume 2 (UNEP, n.d.-b). In these, the authors give detailed explanations on the development of CFs for different impact categories and preliminary recommendations. However, in 2024, a summary of the underlying sources for each impact category was published (Verones et al., 2024). These sources differ from those cited in the two previous reports. Secondly, only a brief overview of what can be found in each publication is provided in the latest summary.

Thirdly, the package has yet to be implemented into any LCA software. According to the creators of GLAM, it will be released to LCA software in March 2025 (Life Cycle Initiative, 2024). From our investigations, we have not yet found any LCA software that have implemented GLAM in time for writing this report. For these reasons, GLAM has not been further analyzed in detail in this study. However, this is an LCIA package that would be interesting to examine in the future, once these details have been sorted out.

4.2 ReCiPe 2016

As mentioned in Section 3, ReCiPe 2016 is a ready-made LCIA package that provides a harmonized implementation of cause-effect pathways for the calculation of both midpoint and endpoint CFs (Huijbregts et al., 2017a). ReCiPe 2016 covers 17 midpoint impact categories and three areas of protection: human health, ecosystem quality and resource scarcity. The method was first introduced in 2008 and updated in 2016, maintaining the three areas of protection. In this package, the connection between environmental mechanisms, represented by midpoint impact categories, and endpoints is established through damage pathways. The damage pathways relevant to ecosystem quality include damage to freshwater species, damage to terrestrial species, and damage to marine species.

The ecosystem quality endpoint includes 10 impact categories related to species and their environments (Huijbregts et al., 2016). When using OpenLCA, the results show 12 impact categories. This can be explained by the fact that the categories climate change and water use both have been divided into two: climate change, freshwater ecosystems and climate change terrestrial systems, as well as water use, aquatic systems and water use, terrestrial ecosystems. In ReCiPe 2016, the endpoint for ecosystem quality is based on the potentially disappeared fraction (PDF) of species over a given area or volume and time, expressed as PDF·m^2·yr for land, or PDF·m^3·yr for freshwater and marine environments. To combine these different ecosystem types into a single comparable metric, ReCiPe 2016 converts all values into the unit species·yr, which represents the equivalent of losing one species from an area for the duration of a year. This metric does not indicate a definite or permanent extinction, but rather the risk of it happening. This calculation is performed by multiplying the PDF-based results by the average species density in each ecosystem type (terrestrial, freshwater, and marine). ReCiPe 2016 has included three different perspectives when it comes to value choices, where each of them groups similar types of assumptions and choices. The individualistic, hierarchist and the egalitarian perspective are covering different time horizons with 20, 100 and 1000 years, which also affects the derived CFs.

The endpoint CF ($CFe_{x,a}$) is calculated from the midpoint CF (CFm_x) with a midpoint-to-endpoint conversion factor, which is constant for each impact category (Huijbregts et al., 2016). In Equation 1, *a* denotes the area of protection, *x* the stressor of concern and "$F_{M \rightarrow E,a}$ " is the conversion factor for area of protection *a.* The value of ecosystem damage is in the end summed to a total for all endpoint values, to get an aggregated score for ecosystem quality.

$$CFe_{x,a} = CF_{m_x} \times F_{M \rightarrow E,a} \quad \textit{(Equation 1)}$$

Climate change
Climate change is caused by the emission of greenhouse gases (GHG) into the atmosphere, increasing the GHG concentration (Huijbregts et al., 2016). This will lead to an increased radiative forcing, as well as increased global mean temperature. In turn, this will affect biomes and natural habitats of species.

The midpoint CF for climate change is the global warming potential (GWP), which is widely used in different LCIA packages. It quantifies the integrated infrared radiative forcing increase of a GHG, expressed in the unit kg CO_2-eq (IPCC, 2013). The equation for the calculation of the midpoint CF, of any GHG and any time horizon, is as follows:

$$GWP_{x,TH} = \frac{AGWP_{x,TH}}{AGWP_{CO_2,TH}} \quad \textit{(Equation 2)}$$

AGWP stands for the Absolute Global Warming Potential and represents the amount of radiative forcing integrated over time caused by the emission of 1 kg of a GHG expressed in

W m^{-2} yr kg^{-1} (Huijbregts et al., 2016). The AGWP for 20 and 100 years can be taken directly from the IPCC report (2013) and for 1000 years it can be calculated, as shown in Equation 3. The *RF* value is the radiative efficiency, *cv* is the substance-specific mass to concentration conversion factor, *LT* is the lifetime of a substance and *TH* is the time horizon.

$$AGWP_{x,TH} = RF_x cv_x LT_x \left(1 - e^{-\frac{TH}{LT_x}}\right) \quad \text{(Equation 3)}$$

For the midpoint-to-endpoint calculation, Equation 4 is used, where the unit for terrestrial and aquatic ecosystems is species·yr/kg CO_2-eq (Huijbregts et al., 2016). At the endpoint level, the impact category is therefore divided into two different parts: global warming for freshwater systems and global warming for terrestrial ecosystems. The $GWP_{x,c}$ is the midpoint CF and the $F_{M\rightarrow E,CC,c,a}$ is the midpoint to endpoint conversion factor for cultural perspective c and area of protection *a*.

$$CFe_{x,c,a} = GWP_{x,c} \cdot F_{M\rightarrow E,CC,c,a} \quad \text{(Equation 4)}$$

Water use

Water use is based on freshwater consumption (Huijbregts et al., 2016). This will lead to a decrease in blue water, that is, water in lakes, rivers, aquifers, which would affect water availability for plants. Also, freshwater fish would be affected due to changed river discharge. The CF at midpoint level for water use is m^3 of water consumed per m^3 of water extracted (Pfister et al., 2009). Extraction refers to the total amount of water withdrawn, regardless of potential return flows to surface water bodies or water-use efficiencies (Huijbregts et al., 2016). Water consumption, in turn, represents the net amount of water permanently lost from the watershed of origin. The calculation for the midpoint CF is shown in Equation 5. The midpoint indicator directly matches the inventory if flows are already reported as consumptive water flows. However, if water flows are reported only as withdrawals or extracted water, a factor must be applied to account for return flows.

$$CF_{mid} = \begin{cases} 1 & if\ inventroy\ in\ m^3\ consumed \\ water\ requirement\ ratio & if\ inventory\ in\ m^3\ withdrawn \end{cases} \quad \text{(Equation 5)}$$

The impact category is divided into water use for terrestrial ecosystems and water use for aquatic ecosystems at endpoint level (Huijbregts et al., 2016). For the midpoint-to-endpoint calculation, the following equations are used, where the unit for terrestrial and aquatic ecosystems is species·yr/ m^3 in Equation 6 and 7. The unit of the CF is first expressed in PDF·m^3/m^2·yr but converted to species·yr/m^3 through the value of species density in each ecosystem. The $NPP_{water\text{-}limited,k}$ in Equation 6 is the water-limited net primary productivity in each pixel *k* of a watershed or country *i*. The P_k is the grid-specific precipitation. The dQ_{mouth} in Equation 7 is the marginal change in the river discharge at the mouth of the river and the *dWC* is the marginal change in consumption. The *dPDF* is the marginal change of species lost associated with the change in the river discharge.

$$CF_i = \frac{\sum_{k=1}^{n} NPP_{water-limited,k}}{\sum_{k=1}^{n} P_k} \quad \text{(Equation 6)}$$

$$CF = \frac{dQ_{mouth}}{dWC} \cdot \left(\frac{dPDF}{dQ_{mouth}} \cdot \mathrm{V}\right) \quad \text{(Equation 7)}$$

Freshwater ecotoxicity

Freshwater ecotoxicity occurs when a chemical is emitted, enters the freshwater compartment, and is exposed to species who take harm (Huijbregts et al., 2016). The CF for ecotoxicity in ecosystems accounts for the environmental persistence, accumulation and toxicity of a chemical. This is also called fate, exposure and effect, which start from the emission of a chemical to the environment and ends with its damage to the ecosystem. The used fate, exposure and effect model in ReCiPe 2016 is the Uniform System for the Evaluation of Substances adapted for LCA (USES-LCA 2.0). The CF at midpoint level for freshwater ecotoxicity is the toxicity potential (TP) expressed in kg 1,4-dichlorobenzene-equivalents (1,4-DCB-eq) in freshwater (van Zelm et al., 2009; 2013). The chemical 1,4-dichlorobenzene is in general used by dividing the calculated potential impact of the chemical by the potential impact of 1,4-DCB emitted to freshwater. The calculation for the compartment-specific ecotoxicological midpoint CF is shown in Equation 8.

$$ETP_{x,i,j,c} = \sum_g \frac{FF_{x,i,j,g,c} \cdot EF_{x,j,c}}{FF_{DCB,ref,j,g,c} \cdot EF_{DCB,j,c}} \quad \text{(Equation 8)}$$

In Equation 8, $ETP_{x,i,j,c}$ is the ecotoxicity potential for the receiving compartment *j* of chemical *x* emitted to compartment *i*, transported to receiving compartment *j*, related to cultural perspective *c*. $FF_{x,i,j,g,c}$ is the fate factor as the marginal change in the steady state mass of substance *x* in an environmental compartment *j* at scale *g* due to a marginal emission in compartment *i* for cultural perspective *c*. The $EF_{x,j,c}$ is the effect factor representing the change in potentially disappeared fraction of species due to a change in the environmental concentration of substance *x* in receiving compartment *j* for cultural perspective *c*.

For the midpoint to endpoint calculation, Equation 9 is used, where the unit for terrestrial, marine and freshwater ecotoxicity is species·yr/ kg 1,4-DCB-eq. The $CFeco_{x,i,j,c}$ is the endpoint CF for ecotoxicity, and $F_{M \to E,ETOX,j,c}$ is the midpoint to endpoint factor for toxicity.

$$CFeco_{x,i,j,c} = ETP_{x,i,j,c} \cdot F_{M \to E,ETOX,j,c} \quad \text{(Equation 9)}$$

Marine ecotoxicity

Marine ecotoxicity occurs due to the same cause-effect chain as freshwater ecotoxicity, but with the difference that the marine environment is affected instead of freshwater. The marine ecotoxicity midpoint CF is, as the freshwater ecotoxicity, expressed as the TP in 1,4-DCB-eq, but in seawater (Huijbregts et al., 2016). The calculation for the compartment-specific ecotoxicological midpoint CF is the same as for freshwater ecotoxicity, but the *ETP* is the ecological toxicity potential for the compartment marine instead of compartment freshwater (Van Zelm et al., 2009; 2013). This is shown in Equation 10.

$$ETP_{x,i,j,c} = \sum_{g} \frac{FF_{x,i,j,g,c} \cdot EF_{x,j,c}}{FF_{DCB,ref,j,g,c} \cdot EF_{DCB,j,c}} \quad \text{(Equation 10)}$$

For the midpoint-to-endpoint calculation, Equation 11 is used, where the unit for terrestrial, marine and freshwater ecotoxicity is species·yr/ kg 1,4-DCB-eq. The *CFeco* and the F_M are the same as in freshwater ecotoxicity.

$$CFeco_{x,i,j,c} = ETP_{x,i,j,c} \cdot F_{M \rightarrow E,ETOX,j,c} \quad \text{(Equation 11)}$$

Terrestrial ecotoxicity

The third ecotoxicity impact in ReCiPe 2016 is terrestrial ecotoxicity. It follows the same cause-effect chain as the previous two, but with industrial soil being exposed to the chemical. The terrestrial ecotoxicity midpoint CF is expressed as 1,4-DCB-eq in industrial soil (Huijbregts et al., 2016). The calculation for the compartment-specific ecotoxicological midpoint CF is the same as for freshwater and marine ecotoxicity, but the *ETP* is the ecological toxicity potential for the compartment terrestrial (van Zelm et al., 2009; 2013).

$$ETP_{x,i,j,c} = \sum_{g} \frac{FF_{x,i,j,g,c} \cdot EF_{x,j,c}}{FF_{DCB,ref,j,g,c} \cdot EF_{DBC,j,c}} \quad \text{(Equation 12)}$$

For the midpoint to endpoint calculation the following equation is used where the unit for terrestrial, marine and freshwater ecotoxicity is species·yr/ kg 1,4-DCB-eq. The *CFeco* and the F_M are the same as in freshwater ecotoxicity.

$$CFeco_{x,i,j,c} = ETP_{x,i,j,c} \cdot F_{M \rightarrow E,ETOX,j,c} \quad \text{(Equation 13)}$$

Freshwater eutrophication

Freshwater eutrophication occurs when nutrients, primarily phosphorus and nitrogen, are released to water bodies or soils, leading to increased nutrient levels (Huijbregts et al., 2016). This leads to numerous ecological effects, increasing the uptake of autotrophs and heterotrophs. Over time, this will lead to an imbalance in the ecosystem, resulting in species loss. The method has chosen to utilize phosphorus for freshwater eutrophication, because phosphorus is generally the limiting nutrient in freshwater ecosystems.

The CF for freshwater eutrophication accounts for the impacts of the rise in nutrient levels in the environment (Huijbregts et al., 2016). The impacts from the emission to freshwater is based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in the water and the species affected due to the phosphorus level rise. The CFs at midpoint level are calculated as shown in Equation 14, where *FEP* is the freshwater eutrophication potential expressed in kg P-eq to freshwater (Helmes et al., 2012). $FF_{x,c,i}$ is the fate factor, and $FF_{P,fw,world\ average}$ is the world average fate factor.

$$FEP_{x,ci} = \frac{FF_{x,c,i}}{FF_{P,fw,world\ average}} \quad \text{(Equation 14)}$$

For the midpoint to endpoint calculation, Equation 15 is used, where the unit for freshwater ecosystems is species·yr/ kg P-eq. The $CFe_{x,i}$ is the endpoint CF for freshwater eutrophication, and $F_{M\rightarrow E,FE}$ is the midpoint to endpoint conversion factor.

$$CFe_{x,i} = FEP_{x,i} \cdot F_{M\rightarrow E,FE} \quad \text{(Equation 15)}$$

Photochemical ozone formation

This impact category is called photochemical ozone formation, since ozone is not directly emitted into the atmosphere, but rather formed by photochemical reactions involving NO_x and non-methane volatile organic compounds (NMVOCs) (Huijbregts et al., 2016). The ozone can then be taken up by plants and have negative effects such as reduction of growth and an acceleration of leaf aging.

The CF for photochemical ozone formation accounts for the emission of NO_x or NMVOC to the environment, uptake and effect on species and damage to terrestrial ecosystems (Huijbregts et al., 2016). The CFs at midpoint level for terrestrial ecosystem damage is calculated as shown in Equation 16. In the equation, the *EOFP* is the ecosystem ozone formation potential expressed in kg NO_x-eq (van Zelm et al., 2016). $FF_{x,i}$ is the fate factor, and $FF_{NOx,world\ average}$ is the world average fate factor of NO_x.

$$EOFP_{x,i} = \frac{FF_{x,i}}{FF_{NOx,world\ average}} \quad \text{(Equation 16)}$$

To calculate the ecosystem fate factor for ozone formation, it is necessary to use *AOT40*, which is the accumulated ozone exposure over a threshold of 40 parts per billion (ppb). The value is then divided by the total change in cumulative ozone concentration *M*, as shown in Equation 17.

$$FF_{x,i\rightarrow g} = \sum_g \frac{\Delta AOT40_g}{\Delta M_{x,i}} \quad \text{(Equation 17)}$$

For the midpoint to endpoint calculation the following equation is used where the unit for terrestrial ecosystems is species·yr/ kg NOx-eq. The $CF_{e,x,i}$ is the endpoint CF for photochemical ozone formation, and the $F_{M\rightarrow E,03}$ is the midpoint to endpoint factor for terrestrial ecosystem damage.

$$CF_{e,x,i} = EOFP_{x,i} \cdot F_{M\rightarrow E,O3} \quad \text{(Equation 18)}$$

Terrestrial acidification

Terrestrial acidification occurs when acidic substances such as NO_x, SO_2 and NH_3 are released into the environment, changing the soil acidity (Huijbregts et al., 2016). Most plant species have a defined optimal pH range, and a deviation from this can be harmful, affecting their growth and survival.

The terrestrial acidification CF includes atmospheric deposition of acidic substances, such as sulphates, phosphates and nitrates and their effect on the acidity in the soil. The impact from the emissions of acidic substances is based on the change in H^+ concentration in the soil and the species affected, which in the end affect the ecosystem. The midpoint CF is calculated as shown in Equation 19, where AP is the acidification potential expressed in SO_2-eq (Roy et al., 2014a). $FF_{x,i}$ is the fate factor for acidification, and $FF_{SO2,world\ average}$ is the world average fate factor for SO_2.

$$AP_{x,i} = \frac{FF_{x,i}}{FF_{SO2,world\ average}} \quad \text{(Equation 19)}$$

To calculate $FF_{x,i}$ for acidification, both the FF for air and soil are needed, as shown in Equation 20.

$$FF_{x,i} = \sum_j FF_{air,x,i\rightarrow j} \cdot FF_{soil,x,j} \quad \text{(Equation 20)}$$

For the midpoint-to-endpoint calculation, Equation 21 is used, where the unit for terrestrial ecosystems is species·yr/ kg SO_2-eq. The $CF_{e,x,i}$ is the CF for terrestrial acidification, and $F_{M\rightarrow E,ACI}$ is the midpoint to endpoint factor.

$$CF_{e,x,i} = AP_{x,i} \cdot F_{M\rightarrow E,ACI} \quad \text{(Equation 21)}$$

Land use

The land use CF includes the relative species loss due to local land use, and specifically land transformation, occupation and relaxation shown in Figure 7 (Huijbregts et al., 2016). During the transformation phase, the original vegetation of the land is removed. During the occupation phase, the land is utilized for a certain period and in the relaxation phase the land is allowed to return to a (semi-) natural state.

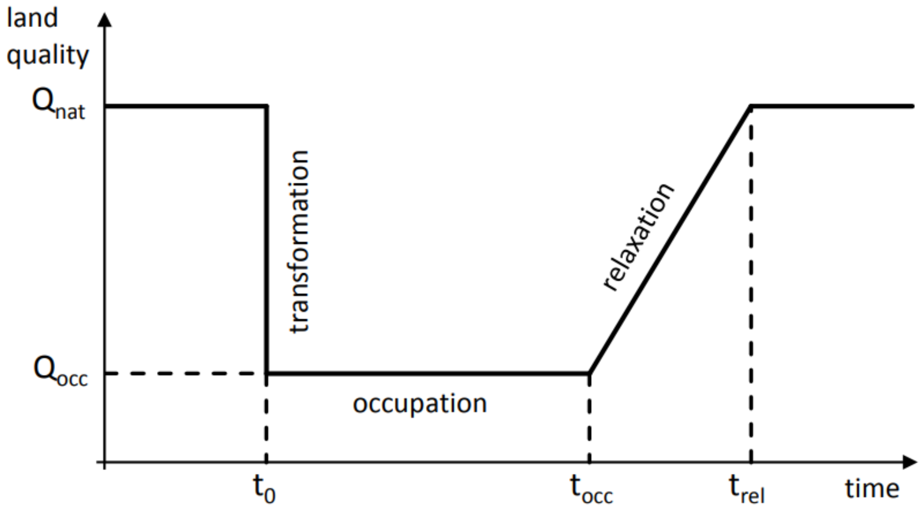

Figure 7. Q_{nat} *shows the original, natural land quality and* Q_{occ} *is the land quality after land transformation.* t_0, t_{occ} *and* t_{rel} *shows the time between transformation, occupation and relaxation (Huijbregts et al. 2016).*

The impacts of land use are based on the change and disturbance that occur when land use intensifies and there is a change of land cover (Huijbregts et al., 2016). This can lead to habitat loss and affect all species living in the area, which damages the ecosystem and the biodiversity. The taxonomic groups used for the calculations or the data on species richness include plants, mammals, birds and invertebrates. Species that are not included are for example reptiles, amphibians and insects. The land use types included for the calculations are used forest, pasture and meadow, annual crops, permanent crops, mosaic agriculture and artificial areas. The artificial areas, in turn, include urban and industrial areas as well as dump sites and railway/road networks. The midpoint CF is calculated as shown in Equation 22, where $CFm_{occ,x}$ is the CF for transformation/occupation expressed in annual crop equivalents (m^2) (de Baan et al., 2013). $S_{rel,x}$ is the relative species loss caused by land use type *x* and $S_{rel,annual\ crop}$ in the denominator is the relative species loss resulting from annual crop production.

$$CFm_{occ,x} = \frac{S_{rel,x}}{S_{rel,annualcrop}} \quad \textit{(Equation 22)}$$

To calculate the relative species loss, the species richness in specific types of natural land covers and human- made land covers is compared. In Equation 23, S_{LU} is the observed species richness of the human-made land covers under land use type *x* in region *i* and S_{REF} is referring to the reference land cover. The reference state is based on the concept of potential natural vegetation, meaning what state the ecosystem would be in after human activities are stopped.

$$S_{rel,x} = 1 - \frac{S_{LU,x,i}}{S_{ref,i}} \quad \textit{(Equation 23)}$$

The *CFm* for land relaxation is calculated from the CF for occupation, multiplied with the constant 0.5 to scale the occupation impact over time, and the recovery time *t*, shown in Equation 24.

$$CFm_{relax,x} = CF_{occ,x} \cdot 0.5 \cdot t_{rel} \quad \textit{(Equation 24)}$$

For the midpoint-to-endpoint calculation, Equation 25 and 26 are used, where the unit for land transformation, occupation and relaxation is species/ m^2 annual crop eq. The $CFe_{occ,x}$ is the endpoint CF for transformation/occupation and the $CFe_{relax,x}$ is the CF for land relaxation. The $F_{M \to E,LU}$ is the midpoint to endpoint conversion factor for land use.

$$CFe_{occ,x} = CFm_{occ,x} \cdot F_{M \to E,LU} \quad \textit{(Equation 25)}$$

$$CFe_{relax,x} = CFm_{relax,x} \cdot F_{M \to E,LU} \quad \textit{(Equation 26)}$$

Marine eutrophication

Marine eutrophication is not part of the original ReCiPe 2016 (Huijbregts et al., 2016). However, it is included in the updated version, ReCiPe 2016 v1.1 (Huijbregts et al., 2017b). Marine eutrophication occurs when nutrients, primarily nitrogen and phosphorus, are released into riverine or marine systems, leading to increased nutrient levels. It is often runoffs and leaching of nutrients from soil or freshwater that end up in the marine system. This causes nutrient enrichment which in turn can cause benthic oxygen depletion, hypoxic waters, anoxia and lastly "dead zones", that result in species loss. The method has chosen to utilize nitrogen for marine eutrophication, because nitrogen is generally the limiting nutrient in marine waters.

The CF for marine eutrophication accounts for the impacts of the rise of dissolved inorganic nitrogen (DIN) in the environment (Huijbregts et al., 2017b). The impacts are based on the transfer of DIN from the soil and freshwater bodies or directly to marine waters, the residence time in marine systems and the dissolved oxygen (DO) depletion, which affects the PDF. The CF at midpoint level is calculated as shown in Equation 27, where *MEP* is the marine eutrophication potential of substance *x* for emission to compartment *c*. $E_{x,c,LME}$ is the fraction of emission for emission *x* in compartment c that ultimately reaches the large marine ecosystem (LME) and the $E_{n,mw,LME}$ is the fraction of nitrogen emission in the compartment marine waters that ultimately reaches the large marine ecosystem. The equation is scaled to the emission of nitrogen emitted to marine water. *XF* is the exposure factor, and *FF* is the fate factor.

$$MEP_{x,c} = \left. \frac{\Sigma(FF_{x,c,LME} \cdot XF_{x,c,LME} \cdot E_{x,c,LME})}{\Sigma E_{x,c,LME}} \middle/ \frac{\Sigma(FF_{N,mw,LME} \cdot XF_{N,mw,LME} \cdot E_{N,mw,LME})}{\Sigma E_{N,mw,LME}} \right.$$

(*Equation 27)*

For the midpoint-to-endpoint calculation, Equation 28 is used, where the unit for marine eutrophication is species·yr/ kg N to marine water-eq. The $CFe_{x,i}$ is the endpoint CF for marine eutrophication, and $F_{M\rightarrow E,ME}$ is the midpoint to endpoint conversion factor.

$$CFe_{x,i} = MEP_{x,i} \times F_{M\rightarrow E,ME} \quad \textit{(Equation 28)}$$

4.3 IMPACT World+

IMPACT World+ is an LCIA package, based on the work of three previous LCIA packages named IMPACT 2002+, LUCAS, and EDIP (Bulle et al., 2019a). It was developed due to the emerging need for a globally regionalized LCIA package, meaning that environmental impacts are assessed with greater spatial accuracy rather than relying on global averages. However, the practical application of this package relies on the availability of site-specific LCI data (Mutel et al., 2018). If this is not available, the package defaults to global average CFs (Bulle et al., 2019b).

IMPACT World+ includes four viewpoints: midpoint level indicator, damage level indicator, damage on areas of protection, and damage on areas of concern (AoC) (Bulle et al., 2019a). In this study, the focus will not be on AoC, so this will not be explained further. The general progression is to go from midpoint to damage level, to area of protection. The four key components included to reach this is:

- Fate Factor (FF) – Describes how a pollutant moves and persists in the environment after release.
- Exposure Factor (XF) – Describes how much of the emitted substance a population or ecosystem is exposed to.
- Exposure-response Factor (EXF) – Describes the negative consequences of the emitted substance to a population or ecosystem.
- Severity Factor (SF) – Converts the previous results into a common unit.

An additional factor called "effect factor" is also mentioned in the framework. There is no detailed explanation of what this consists of in the report, but after personal correspondence with the author Cécile Bulle, it is explained to correspond to EXF·SF (personal communication, April 25, 2025).

Not all factors are included in every midpoint equation, as the relevance of each component depends on the environmental mechanism and impact pathway of the specific impact category. The position of the midpoint on the cause-effect chain furthermore varies among impact categories.

For the damage-level indicator, all four key components, FF, XF, EX and SF, are applied (Bulle et al., 2019a). This results in all damage-level indicators having the same unit: PDF·m^2·yr. Once damage level results are calculated, they are grouped according to the area of protection they contribute to. The relevant damage scores are then added together, resulting in a total damage score for that area of protection.

The IMPACT World+ package was first introduced in 2019 and has since been updated with new versions, the current being version 2.1. Some of the impact categories available today were not included in the original version. These newer additions reflect ongoing developments in environmental modeling and aim to improve the LCIA package's ability to capture a broader range of environmental and health-related impacts. Due to this, not all documentation and detail about the current impact categories can be found in the original publication, as some elements have been introduced or refined in later updates. The package currently includes 17 impact categories at damage level. However, water availability is divided int two parts: water availability, freshwater ecosystems and terrestrial ecosystems.

In the following section, a brief overview of all midpoint and damage levels connected to ecosystem quality in the newest version of IMPACT World+ 2.1, are presented. The package combines external data sources with an internal modeling framework. For midpoint indicators, IMPACT World+ frequently relies on CFs adapted from previous models and established methods. However, instead of simply importing these values, IMPACT World+ also provides the underlying equations used to derive these CFs. In some cases, the authors have made modifications of, or additions to, these existing models. The purpose of this is to show how the CFs were integrated into the overall framework. The CFs on midpoint level quantify the potential environmental pressure, but to capture the resulting ecological damage, the next step is to calculate at damage level. The damage indicators are primarily developed within the LCIA package itself. The formulas will be presented in two tables, one for midpoint level and one for damage level. To facilitate the understanding of the components and when the framework changes formula between midpoint and damage point, color coding has been used. All formulas at midpoint level are marked in green. In the table for damage level, formulas that are the same at both the midpoint and damage level are also marked in green, while new formulas used on damage level are marked in blue.

Climate change

The IMPACT World+ package has chosen to divide climate change into two parts at midpoint level; short term and long term, in order to account for its various impact on different time scales (Bulle et al., 2019a). Short term impacts include fast temperature rises, which species need fast adaptation to, while long term impacts include gradual changes, such as sea level rise (Bulle et al., 2019b). The method uses Global Temperature Potential for a 100-year time horizon (GTP100) for long term climate change, and Global Warming Potential for a 100-year time horizon (GWP100) for short term climate change. The unit is kg CO_2-eq for both.

For damage level, GTP100 cannot be used since it only reflects the temperature rise at one point in time (Bulle et al., 2019b). To account for the cumulative effects, absolute GTP (aGTP) is used. The unit is PDF·m^2·yr.

Table 1. A summary of the equations used for midpoint level for climate change.

Midpoint level indicator	**FF**	**XF**	**EXF**	**SF**
Climate change, short term (GWP100)	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}{Mass_{emitted}}$	$\frac{\int_{t1}^{t2} \Delta Radiative\ forcing\ \mathrm{dt}}{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}$	-	-
Climate change, long term (GTP100)		$\frac{\Delta Temperature\ after\ 100\ years}{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}$	-	-

Table 2. A summary of the equations used for damage level for climate change.

Damage level indicator	**FF**	**XF**	**EXF**	**SF**
Climate change	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}{Mass_{emitted}}$	$\frac{\int_{t1}^{t2} \Delta Temperature\ \mathrm{dt}}{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}$	$\frac{Damage_{EQ}}{\int_{t1}^{t2} \Delta Temperature\ \mathrm{dt}}$	

Marine acidification

Marine acidification occurs when CO_2 emissions dissolve in marine waters, forming carbonic acid that increases the concentration of H^+ ions and thereby the acidity (Bulle et al., 2019b). Consequently, it becomes harder for marine species like coral and plankton to build and maintain calcium carbonate structure, making them more vulnerable and increasing the risk of biodiversity loss.

Marine acidification does not have its own midpoint level indicator in the package, only a damage level (Bulle et al., 2019a). Instead, the method has used long term climate change as a proxy midpoint for acidification. This is due to the assumption that only CO_2 emissions affect marine acidification. At damage level, the XF estimates how increased atmospheric CO_2 lowers ocean pH over time based on Azevedo et al. (2015).

Table 3. A summary of the equations used for midpoint level for marine acidification.

Midpoint level indicator	**FF**	**XF**	**EXF**	**SF**
Climate change, long term	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}{Mass_{emitted}}$	$\frac{\Delta Temperature\ after\ 100\ years}{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}$	-	-

Table 4. A summary of the equations used for damage level for marine acidification.

Damage level indicator	**FF**	**XF**	**EXF**	**SF**
Marine acidification	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}{Mass_{emitted}}$	$\frac{\int_{t1}^{t2} \Delta pH\ \mathrm{dt}}{\int_{t1}^{t2} \Delta Mass\ in\ the\ atmosphere\ \mathrm{dt}}$	$\frac{PAF \cdot \mathrm{Area} \cdot \mathrm{Time}}{\int_{t1}^{t2} \Delta pH\ \mathrm{dt}}$	$\frac{Damage_{EQ}}{PAF \cdot \mathrm{Area} \cdot \mathrm{Time}}$

Freshwater and terrestrial acidification

Acidifying substances such as NO_x, NH_3 and SO_2 emitted to the atmosphere will ultimately settle on land and water (Bulle et al., 2019b). The substances may have traveled far distances, and when settling down it will change the acidity level (pH) of the space in question, i.e. freshwater or terrain. Since species are adapted to certain acidity levels, a change in this may be harmful and affect the organisms in the area. The IMPACT World+ package contains CFs from Roy et al. (2012a; 2014a) for terrestrial acidification, and CFs from Roy et al. (2012b; 2014b) for freshwater acidification, for both midpoint and damage level.

The midpoint level models how emissions of NO_x, NH_3 and SO_2 affect the pH levels in soil and freshwater (Bulle et al., 2019b). The unit at midpoint level is kg SO_2-eq.

At the damage level, impacts on ecosystem quality are expressed in PDF·m²·yr (Bulle et al., 2019b). The method combines midpoint CFs with EXF and SF. For terrestrial acidification, the effect factor estimates how changes in soil pH impact the diversity of vascular plant species. In the case of freshwater acidification, it quantifies the potential loss of fish species based on changes in water pH.

Table 5. A summary of the equations used for midpoint level for freshwater and terrestrial acidification.

Midpoint level indicator	**FF**	**XF**	**EXF**	**SF**
Freshwater acidification	$\frac{Mass_{deposited}}{Mass_{emitted}}$	$\frac{\int_{t1}^{t2} \Delta pH \; \mathrm{dt}}{Mass_{deposited}}$	-	-
Terrestrial acidification				

Table 6. A summary of the equations used for damage level for freshwater and terrestrial acidification.

Damage level indicator	**FF**	**XF**	**EXF**	**SF**
Freshwater acidification	$\frac{Mass_{deposited}}{Mass_{emitted}}$	$\frac{\int_{t1}^{t2} \Delta pH \; \mathrm{dt}}{Mass_{deposited}}$	$\frac{PAF \cdot \mathrm{Area} \cdot \mathrm{Time}}{\int_{t1}^{t2} \Delta pH \; \mathrm{dt}}$	$\frac{Damage_{EQ}}{PAF \cdot \mathrm{Area} \cdot \mathrm{Time}}$
Terrestrial acidification				

Marine eutrophication

Eutrophication occurs due to an increase of nutrients released to water (Bulle et al., 2019b). For marine eutrophication, the limiting nutrient is nitrogen. Excess release of nitrogen increases the growth of primary producers, and in turn decreases the amount of oxygen.

Values for FF were obtained from Roy et al., (2012b), while the effect factor where empirically found to be 12.5 PDF·m²·yr. This value was established by examining the ratio between nitrogen loads and the extent of observed eutrophication in the highly affected regions the Gulf of Mexico, Baltic Sea and Chesapeake Bay. For both marine and freshwater eutrophication, the XF was assumed to be 1, since effects are based directly on concentration in water rather than on uptake by organisms (Cécile Bulle, Personal communication, April 28, 2025). As a result, the XF and EXF get a unified equation. The unit is kg N N-lim-eq.

Table 7. A summary of the equations used for midpoint level for marine eutrophication.

Midpoint level indicator	**FF**	**XF**	**EXF**	**SF**
Marine eutrophication	$\frac{Mass_{deposited}}{Mass_{emitted}}$	$\frac{PDF \cdot \mathrm{Area} \cdot \mathrm{Time}}{Mass_{deposited}}$		-

Table 8. A summary of the equations used for damage level for marine eutrophication.

Damage level indicator	**FF**	**XF**	**EXF**	**SF**
Marine eutrophication	$\frac{Mass_{deposited}}{Mass_{emitted}}$	$\frac{PDF \cdot \text{Area} \cdot \text{Time}}{Mass_{deposited}}$		$\frac{Damage_{EQ}}{PDF \cdot \text{Area} \cdot \text{Time}}$

Freshwater eutrophication

Freshwater eutrophication is a result of excess phosphorus release (Bulle et al., 2019b). Only the FF represents the CF in this case, which is derived from Helmes et al. (2012), and represents the amount of phosphorus accumulation in freshwater ecosystems per kilogram of phosphorus released. The unit is kg PO_4 P-lim eq. To generate the damage level, they multiply the CF with an EF of 11.4 PDF·m^2·yr/kg PO_4^{3-}eq based on Tirado-Seco (2005).

Table 9. A summary of the equations used for midpoint level for freshwater eutrophication.

Midpoint level indicator	**FF**	**XF**	**EXF**	**SF**
Freshwater eutrophication	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ \text{dt}}{Mass_{emitted}}$	-	-	-

Table 10. A summary of the equations used for damage level for freshwater eutrophication.

Damage level indicator	**FF**	**XF**	**EXF**	**SF**
Freshwater eutrophication	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ \text{dt}}{Mass_{emitted}}$	$\frac{PAF \cdot \text{Area} \cdot \text{Time}}{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ \text{dt}}$		$\frac{Damage_{EQ}}{PAF \cdot \text{Area} \cdot \text{Time}}$

Freshwater ecotoxicity

Freshwater ecotoxicity occurs when toxic substances are released and reach freshwater, causing toxic effects on ecosystems (Bulle et al., 2019b). IMPACT World+ has chosen to incorporate CFs from the USEtox model to derive midpoint values. USEtox is a model designed to evaluate the ecotoxicological impacts on human health and freshwater, by providing scientific validated CFs (USEtox, n.d.). The used unit is called comparative toxic units (CTUe) and is equal to PAF·m^3·day.

To go from midpoint to damage level, a generic SF of 0.5 is used, which converts PAF to PDF (Bulle et al., 2019b). This is based on the assumption that 50% of species initially affected by the exposure will ultimately be lost from the ecosystem.

Table 11. A summary of the equations used for midpoint level for freshwater ecotoxicity.

Midpoint level indicator	**FF**	**XF**	**EXF**	**SF**
Freshwater ecotoxicity	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment}{Mass_{emitted}}$	$\frac{Mass_{bioavailable}}{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ dt}$	$\frac{PAF \cdot \text{Volume} \cdot \text{Time}}{Mass_{bioavailable}}$	-

Table 12. A summary of the equations used for damage level for freshwater ecotoxicity.

Damage level indicator	**FF**	**XF**	**EXF**	**SF**
Freshwater ecotoxicity	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ \text{dt}}{Mass_{emitted}}$	$\frac{Mass_{bioavailable}}{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ dt}$	$\frac{PAF \cdot \text{Volume} \cdot \text{Time}}{Mass_{bioavailable}}$	$\frac{Damage_{EQ}}{PAF \cdot \text{Area} \cdot \text{Time}}$

Terrestrial and marine ecotoxicity

Marine and terrestrial ecotoxicity are included as interim impact categories in IMPACT World+ (Bulle et al., 2019b). This means they are based on preliminary models, mainly adapted from USEtox, but are not yet fully developed. Both impact categories are presented on damage level, but not at midpoint.

Table 13. A summary of the equations used for damage level for terrestrial and marine ecotoxicity.

Damage level indicator	**FF**	**XF**	**EXF**	**SF**
Terrestrial ecotoxicity	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ \text{dt}}{Mass_{emitted}}$	$\frac{Mass_{bioavailable}}{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ dt}$	$\frac{PAF \cdot \text{Volume} \cdot \text{Time}}{Mass_{bioavailable}}$	$\frac{Damage_{EQ}}{PAF \cdot \text{Area} \cdot \text{Time}}$
Marine ecotoxicity				

Plastic physical effects on biota

Plastic physical effects on biota is a new indicator in version 2.1 of IMPACT World+, which focuses on the effects plastic waste has on organisms in aquatic environments (IMPACT World+, n.d.-a). Plastic waste can harm organisms by entanglement, ingestion or smothering (Woods et al., 2021). Entanglement can lead to physical injury, compromised mobility, starvation and reduced reproduction. Ingestion may block the digestive tract, leading to starvation and death. Smothering, often caused by sunken plastic waste, can cause anoxic or hypoxic conditions in benthic ecosystems and thereby change the function of the ecosystem. Important to note here is that this midpoint impact category only covers physical effects, while chemical impacts are instead covered under ecotoxicity (Corella-Puertas, 2023).

CFs for this impact category have been derived from the work of MarILCA (IMPACT World+, n.d.-a). The working group has developed CFs for 11 polymers, 3 shapes and 5 sizes (Corella-Puertas, 2023). They have chosen to combine XF and EF into a common factor called exposure and effect factor (EEF). The EEF has a value of 1067.5 PAF·m^3. To get the FF, the method follows the USEtox model. The unit of the midpoint CF is PAF·m^3·day.

To go from midpoint level to damage level, the midpoint CF is multiplied by the SF, in PDF/PAF, divided by the water depth in meter.

Table 14. A summary of the equations used for midpoint level for plastics physical effects on biota.

Midpoint level indicator	**FF**	**XF**	**EF**	**SF**
Plastics physical effects on biota	$\frac{kg_{in\ copmartment}}{kg_{emitted}/year}$	$\frac{PAF \cdot m^3}{kg_{in\ compartment}}$		-

Table 15. A summary of the equations used for damage level for plastic physical effects on biota.

Damage level indicator	**FF**	**XF**	**EF**	**SF**
Plastics physical effects on biota	$\frac{kg_{in\ copmartment}}{kg_{emitted}/year}$	$\frac{PAF \cdot m^3}{kg_{in\ compartment}}$		$\frac{PDF}{PAF \cdot m}$

Photochemical oxidant/ozone formation

In IMPACT World+, the impact category previously referred to as photochemical oxidant formation is called photochemical ozone formation, both at midpoint and damage level (IMPACT World+, n.d.-a). This impact category considers ground-level ozone that is formed, and the problems it can cause (Bulle et al., 2019b). Ozone is not released directly into the air; it forms when certain air pollutants, like NMVOCs and carbon monoxide, mix with NO_x in sunlight. This happens in the lower part of the atmosphere, close to Earth's surface. The ozone that forms can be harmful to both human health and the environment.

IMPACT World+ is using the same method as ReCiPe 2016 (Bulle et al., 2019b). In the original report by Bulle et al. (2019), this impact category was associated only with human health impacts and not with ecosystem quality. Therefore, no equations related to ecosystem quality were presented. However, in the latest version of IMPACT World+, the impact is now also considered relevant to the ecosystem quality. No specified equation has been provided for this impact category.

Land transformation and occupation, biodiversity

In IMPACT World+, a distinction is made between land transformation and land occupation (Bulle et al., 2019b). Land transformation refers to conversion of natural land, while land occupation refers to ongoing use of land in a modified state, preventing it from returning to its natural condition. The method applies CFs from de Baan et al. (2013).

The unit for land transformation is m^2 arable land eq, and the unit for land occupation is m^2 arable land eq·yr.

Table 16. A summary of the equations used for both midpoint and damage level for land transformation and land occupation.

Midpoint and damage level indicator	**FF**	**XF**	**EXF**	**SF**
Land transformation, biodiversity	$\frac{Area_{occupied} \cdot \text{Time}}{Area_{Transformed}}$	$\frac{Damage_{EQ}}{Area_{occupied} \cdot \text{Time}}$		
Land occupation, biodiversity	$\frac{Damage_{EQ}}{Area_{occupied} \cdot \text{Time}}$			

Ionizing radiation

Ionizing radiation refers to radioactive emissions, which can cause damage to ecosystems (Bulle et al., 2019b). While this impact category has a midpoint indicator in IMPACT World+, it is not linked to ecosystem quality at that level. So, in this report, only the damage level indicator will be considered.

Table 17. A summary of the equations used for damage level for ionizing radiation.

Damage level indicator	**FF**	**XF**	**EF**	**SF**
Ionizing radiation	$\frac{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ \ compartment\ \text{dt}}{Mass_{emitted}}$	$\frac{PAF \cdot \text{Volume} \cdot \text{Time}}{\int_{t1}^{t2} \Delta Mass\ in\ receiving\ compartment\ \text{dt}}$		$\frac{Damage_{EQ}}{PAF \cdot \text{Volume} \cdot \text{Time}}$

Fisheries impacts

The fisheries impact category is a relatively new addition to LCIA and focuses on the direct effects of fishing on marine biodiversity, thus not taking freshwater fishing into account (Stanford-Clark et al., 2024). Overfishing is among the big drivers of biodiversity loss in the marine environment, affecting ecosystem services. Unlike previous approaches that mainly considered effects on fish population as indirect results of emissions or fuel use, this method considers how the removal of biomass from the ocean through fishing affects the quality of marine ecosystems.

So far, this impact category is only available at damage level (CIRAIG, n.d.). The CFs are based on the work by Stanford-Clark et al. (2024). The FF is derived by dividing K, the carrying capacity of a population in its habitat, with rB, the intrinsic growth rate multiplied by the stock biomass. EF is derived by dividing C, the catch, with rB^2. Combined, they represent the potential biodiversity loss per unit of fish caught. The unit is available in both species·yr and PDF·yr, none of which are consistent with the IMPACT World+ framework. To convert the CF into the harmonized unit PDF·yr·m^2, the CF was first divided by *the species richness per FAO (Food and Agriculture Organization) fishing region (S)*, and then divided by *the surface area of said FAO region (A)* (CIRAIG, n.d.).

Table 18. A summary of the equations used for damage level for fisheries impacts.

Damage level indicator	**FF**	**XF**	**EF**	**SF**
Fisheries impacts	$\frac{K}{rB}$	$\frac{C}{rB^2}$		$\frac{1}{S * A}$

Water scarcity and water availability

In IMPACT World+, water-related impacts are addressed through two distinct impact categories: water scarcity at the midpoint level and water availability at the damage level (Bulle et al., 2019b). Water availability is further divided into freshwater and terrestrial ecosystems. Water scarcity is assessed using the AWARE method, estimating how much water remains in a watershed after meeting human and ecosystem demands. The unit is m^3 world-eq.

Although water scarcity and water availability are not part of the same cause-effect chain in IMPACT World+, they are conceptually linked (Bulle et al., 2019b). Water scarcity highlights regions under pressure from competing water uses, while water availability at the damage level captures the potential consequences of water deprivation on ecosystem quality.

Table 19. A summary of the equations used for midpoint level for water scarcity.

Midpoint level indicator	**FF**	**XF**	**EF**	**SF**
Water scarcity	$\frac{Increased\ relative\ deprivation\ potential}{Volume_{consumed}}$	-	-	-

Table 20. A summary of the equations used for damage level for water availability for freshwater and terrestrial ecosystem.

Damage level indicator	**FF**	**XF**	**EF**	**SF**
Water availability, freshwater ecosystem	$\frac{\int_{t1}^{t2} \Delta river\ discharge\ \mathrm{dt}}{Volume_{dissipated}}$	$\frac{PAF \cdot \mathrm{Volume} \cdot \mathrm{Time}}{\int_{t1}^{t2} \Delta river\ discharge\ \mathrm{dt}}$		$\frac{Damage_{EQ}}{PAF \cdot \mathrm{Volume} \cdot \mathrm{Time}}$
Water availability, terrestrial ecosystem	$\frac{\int_{t1}^{t2} \Delta groundwater\ depth\ \mathrm{dt}}{Volume_{dissipated}}$	$\frac{\int_{t1}^{t2} \Delta soil\ moisture\ \mathrm{dt}}{\int_{t1}^{t2} \Delta groundwater\ depth\ \mathrm{dt}}$	$\frac{PNOF}{\int_{t1}^{t2} \Delta soil\ moisture\ \mathrm{dt}}$	$\frac{Damage_{EQ}}{PNOF}$

Thermally polluted water

Thermally polluted water refers to water that has been artificially heated before being released into natural water bodies (Verones et al., 2010). This typically occurs when water is used for cooling in power plants and industrial facilities, and then discharged at a higher temperature than the receiving water body. This can negatively influence aquatic species, which often have a narrow temperature range at which they can operate. Higher water temperatures can cause faster digestion and thereby higher food demand, but also breakdown of nervous system tissue.

This impact category is only addressed at damage level and is based on the work of Verones et al. (2010).

Table 21. A summary of the equations used for damage level for thermally polluted water.

Damage level indicator	**FF**	**XF**	**EF**	**SF**
Thermally polluted water	$\frac{\int_{t1}^{t2} \Delta river\ temperature\ \mathrm{dt}}{Volume_{cooling\ water}}$	$\frac{PDF \cdot \mathrm{Volume} \cdot \mathrm{Time}}{\int_{t1}^{t2} \Delta river\ temperature\ \mathrm{dt}}$		$\frac{Damage_{EQ}}{PDF \cdot \mathrm{Volume} \cdot \mathrm{Time}}$

4.4 LC-IMPACT

LC-IMPACT is an LCIA package that was developed to meet the need of a regionalized approach (Verones et al., 2020a). Unlike some older LCIA packages that utilize global averages, LC-IMPACT uses location-specific data, allowing for more specific assessment of environmental impacts in different geographical places. The degree of spatial variability differs across the various impact categories, depending on their need for spatial detail. Climate change has CFs only on a global level, since the effects are global, whereas CFs for impact categories like water stress are available on local level, as they have location-specific impacts.

The LCIA package has three areas of protection: human health, ecosystem quality and resources, and focus will, as in the previous LCIA packages, remain on ecosystem quality in this study. As of right now, the package does not include any CFs at midpoint level, only at endpoint (Verones et al., 2020a). The reason for this is, according to the authors, that midpoints do not exist in a consistent way for all impact categories. The package provides one general equation for CFs, but since each environmental issue (acidification, eutrophication, land use, etc.) works through different mechanisms and data, the specific implementation of that general formula varies for each impact category. The general equation for CFs for ecosystem quality in LC-IMPACT can be seen in Equation 29. VF stands for vulnerability factor, EF for effect factor, XF for exposure factor and FF for fate factor (Verones et al., 2020b). The vulnerability factor can vary between 0 and 1. The higher the score, the more vulnerable the species.

$$CF_{ecosystem\ quality} = VF \cdot \mathrm{EF} \cdot \mathrm{XF} \cdot \mathrm{FF} \quad \textit{(Equation 29)}$$

Water stress

Freshwater is a limited resource, with humans using it for activities like irrigation while ecosystems rely on it to sustain their natural functions (Verones et al., 2020b). Human use of water is expected to rise, which may affect ecosystems and biodiversity. The authors of LC-IMPACT have decided to measure biodiversity impacts of water consumption two ways: for aquatic and riparian (i.e. areas along rivers and streams) habitats where water consumption in wetlands is utilized as a proxy, and for terrestrial habitats where vascular plants have been utilized as a proxy.

For aquatic and riparian systems, the CF is calculated based on four components: the FF, which estimates changes in wetland area due to water consumption, the EF, which represents potential species loss per square meter or wetland, species richness (S), and vulnerability score (VS), that indicates how sensitive species are to change (Verones et al., 2020b). The VS is based on the threat level and geographical range areas of species from IUCN. The calculation of the CF is presented in Equation 30. The CF for terrestrial habitats follows a similar structure, as seen in Equation 31, but due to lack of data it is assumed that VS is 1, and the factor is therefore not shown in the equation. The unit for both CFs is PDF·yr/m^3.

$$CF_{end,i,t} = \frac{\sum_{i,k=1}^{n} FF_{k,t} \cdot EF_{k,t}}{S_t \cdot VS_t} \quad \textit{(Equation 30)}$$

$$CF_{end,w} = \frac{FF_w \cdot EF_w}{S_{plants}} \quad \textit{(Equation 31)}$$

Climate change

In LC-IMPACT, climate change impacts on ecosystem quality are assessed by linking GHG emissions to temperature increases and their consequences for species survival (Verones et al., 2020b). Unlike other impact categories, which are region-specific, climate change effects are global due to temperature increase being widespread. The CF is considering global warming potential (GWP), temperature change per unit of emissions (δTEMP), and species loss per degree of warming (EF). The CF equation for climate change can be seen in equation 32, and the unit is PDF·yr/kg.

$$CF_{end,x,TH,AOP} = GWP_{x,TH} \cdot \delta\mathrm{Temp}_{CO_2 TH} \cdot EF_{AOP} \quad \textit{(Equation 32)}$$

Photochemical ozone formation

In LC-IMPACT, photochemical ozone formation is assessed by quantifying the disappearance of plant species, through damage caused by ozone (Verones et al., 2020b). The CF equation consists of two parameters: FF and EF. FF describes how emissions of an ozone precursor *x* in region *i*, contribute to ozone exposure in the grid cell *g*. EF then quantifies the impact of the ozone exposure in cell grid *g* on the natural vegetation *n*. The CF equation for photochemical ozone formation can be seen in Equation 33, and the unit is PDF·yr·kg^{-1}.

$$CF_{ECO,x,i} = \sum_g \sum_n \left(FF_{x,i \to g} \cdot EF_{n,g}\right) \quad \textit{(Equation 33)}$$

Freshwater eutrophication

In LC-IMPACT, freshwater eutrophication is modeled through two main paths: emission of phosphorus to soil, which can later leach into freshwater, and erosion of soil to freshwater (Verones et al., 2020b). The CF can be calculated in two steps, Equation 34 calculates the CF on a local scale, while Equation 35 aggregates them into one CF at ecoregion level. FF is the fate factor that describes how much of the emitted substance to compartment *e* in grid cell *i*, is transported to another grid cell *j* in the same ecoregion *r*. EF is the average effect factor for the grid cell *j* in ecoregion *r*. *W* is then a weighting factor of a grid cell *j* in ecoregion *r*. The unit is PDF·yr·kg^{-1} or PDF·yr·m^{-2}·yr^{-1} for erosion.

$$CF_{FW,e,i\in r} = \sum_{j\in r} FF_{e,i,j\in r} \cdot \overline{EF_{j\in r}} \quad \textit{(Equation 34)}$$

$$CF_{FW,e,r} = \frac{1}{\sum_{i\in r} w_{i\in r}} \sum_{i\in r} w_{i\in r} \cdot CF_{FW,e,i\in r} \quad \textit{(Equation 35)}$$

Marine eutrophication

Marine eutrophication is caused by excess nitrogen leaching into marine waters (Verones et al., 2020b). In LC-IMPACT, the impact pathway focuses on waterborne emissions of nitrogen, excluding airborne sources. The CF is calculated as shown in Equation 36. FF is the fate factor for nitrogen emissions from country *i* to the receiving marine ecosystem *j*, through the emission route *k*. XF, EF and VS then represent the receiving marine ecosystem *j*. The unit is PDF·yr·kgN^{-1}.

$$CF_{end,ijk} = \sum_{j} FF_{ijk} \cdot XF_j \cdot EF_j \cdot VS_j \quad \textit{(Equation 36)}$$

Land stress

Just like previous methods, LC-IMPACT has taken two land use types into consideration: land transformation and land occupation (Verones et al., 2020b). The CFs are available for both continent, country and 804 different ecoregions. The package incorporated the countryside species-area relationship (SAR) model developed by Chaudhary et al. (2015). This is a development of the work from de Baan et al. (2013), which was utilized in both ReCiPe 2016 and IMPACT World+. The method includes both marginal and average CFs (Verones et al., 2020b). The marginal CF is commonly used to evaluate the impact of additional land use, while the average CF represents the overall impacts of land use within a region.

The formula for CF for regional average occupation is shown in Equation 37, where *S* is the species lost per region *j*, *a* is the allocation factor and *A* is the area occupied by the land use type *i*. The unit of the CF is regional species lost/m^2.

$$CF_{avg,occ,t,i,j} = \frac{\Delta S_{lost,t,j} \cdot a_{i,j}}{A_{i,j}} \quad \textit{(Equation 37)}$$

The formula for CF for regional marginal occupation can be seen in Equation 38. *S* and *a* are the same as in Equation X, p is the relative frequency by land use type *i* and per region *j*, and A_{lost} is the marginal increase in human used area (Verones et al., 2020b). The unit is regional species lost/m^2.

$$CF_{marg,occ,t,i,j} = \frac{a_{i,j} \cdot \Delta S_{lost,t,j}}{p_{i,j} \cdot \Delta A_{lost,t,j}} \quad \text{(Equation 38)}$$

The CF for land transformation is calculated as shown in Equation 39. The occupation CF from Equation X is multiplied by half of the regeneration time *t* (Verones et al., 2020b). The unit of the CF is regional species loss·years/m^2.

$$CF_{trans,t,i,j} = 0.5 \cdot CF_{occ,t,i,j} \cdot t_{reg,t,i,j} \quad \text{(Equation 39)}$$

Terrestrial acidification

The terrestrial acidification impact pathway in LC-IMPACT includes deposition of nitrogen oxides, ammonia and sulfur dioxide which changes the soil chemical properties and increases the H^+ concentration in the soil (Verones et al., 2020b). The CF at endpoint level is shown in Equation 40, where *AF* is the atmospheric fate factor, *SF* is the soil sensitivity factor and *EF* is the effect factor.

$$CF_{end,i,p} = \sum_{j,p} AF_{i \to j,p} \cdot SF_{j,p} \cdot EF_j \quad \text{(Equation 40)}$$

Freshwater ecotoxicity

Many emissions and chemicals have the ability to cause toxic impacts in species which affect ecosystems. The impact pathway for ecotoxicity in LC-IMPACT includes the environmental fate of a chemical, the ecosystem exposure, the increase in potentially affected fraction of species and lastly the ecosystem health damage (Verones et al., 2020b). The LC-IMPACT package has based their impact category on USEtox. The ecotoxicity for ecosystem quality is defined in terms of PDF integrated over time per kg emitted chemical to a given environmental compartment, PDF·m^3 $_{\text{exposure medium}}$ ·day. The calculation for the ecosystem CF at endpoint level is shown in Equation 41.

$$CF^e = FF \cdot XF^e \cdot EF^e \cdot DF^e \quad \text{(Equation 41)}$$

The fate factor *FF* in the equation is linking the chemical mass emitted per day in a compartment and the chemical mass in a given environmental compartment. The ecosystem exposure factor XF^e in the equation represents the bioavailability of chemicals to organisms. The effect factor EF^e links the potential of the bioavailable fraction of a chemical to cause toxic effects. The damage factor DF^e is expressed in PDF/PAF and links the potentially disappeared fraction of species to the potentially affected fraction of species.

Marine ecotoxicity

Marine ecotoxicity is as the freshwater ecotoxicity calculated through the CF at endpoint level with the fate factor, exposure factor, effect factor and damage factor, shown in Equation 42 (Verones et al., 2020b). For aquatic compartments bioavailability is calculated by using *XF* as the truly dissolved fraction of a chemical in freshwater. The unit of the CF is $\text{PDF}\cdot\text{m}^3_{\text{exposure medium}}\cdot\text{day}$.

$$CF^e = FF \cdot XF^e \cdot EF^e \cdot DF^e \quad \textit{(Equation 42)}$$

Terrestrial ecotoxicity

Terrestrial ecotoxicity is, as the freshwater and marine ecotoxicity, calculated through the CF at endpoint level with the fate factor, exposure factor, effect factor and damage factor, shown in Equation 43 (Verones et al., 2020b). The unit of the CF is $\text{PDF}\cdot\text{m}^3_{\text{exposure medium}}\cdot\text{day}$.

$$CF^e = FF \cdot XF^e \cdot EF^e \cdot DF^e \quad \textit{(Equation 43)}$$

4.5 Method comparison

Table 22 summarizes the studied LCIA packages. For each impact category, the sources the CFs are based on, unit of midpoint indicator, and unit of endpoint indicator are provided. The table is color coded. Green indicates that the impact category is based on the same source/s. Blue indicates that the impact category only exists in one package. Red indicates that the impact categories, while having the same name and meaning, are based on different sources.

Table 22. A summary of ReCiPe 2016, IMPACT World + and LC-IMPACT. The underlying sources the method is based on, the unit of the midpoint (if existent), and the unit of the endpoint is presented.

Impact category	**ReCiPe (2016)**	**IMPACT World+ (2019)**	**LC-IMPACT (2020)**
Global warming / Climate change	IPCC report 5 (2013) Joos et al. (2013) Hanafiah et al. (2011) Urban (2015) Midpoint: [kg CO_2-eq] Endpoint: [Species·yr]	Levasseur et al. (2016) Joos et al. (2013) Myhre et al. (2013) (IPCC report 5) Midpoint: [kg CO_2-eq (long + short)] Endpoint: [PDF·m^2·yr]	Urban (2015) Joos et al. (2013) IPCC report 5 (2013) Hanafiah et al. (2011) Endpoint: [PDF·yr]
Marine acidification	-	Azevedo et al. (2015) Endpoint: [PDF·m^2·yr]	-

Terrestrial acidification	Roy et al. (2014a) Midpoint: [kg SO_2-eq] Endpoint: [Species·yr]	Roy et al. (2014a) Roy et al. (2012a) Roy et al. (2012b) Midpoint: [kg SO_2-eq] Endpoint: [PDF·m^2·yr]	Roy et al. (2014a) Azevedo et al. (2013a) Endpoint: [PDF·yr]
Freshwater acidification	-	Roy et al. (2012b) Roy et al. (2014b) Midpoint: [kg SO_2-eq] Endpoint: [PDF·m^2·yr]	-
Water use / Water scarcity and water availability / Water stress	Pfister et al. (2009) Hanafiah et al. (2011) Midpoint: [m^3] Endpoint: [Species·yr]	Boulay et al. (2018) (AWARE) Hanafiah et al. (2011) van Zelm et al. (2011) Midpoint: [m^3 world-eq /m^3] Endpoint: [PDF·m^2·yr]	Verones et al. (2017a) Endpoint: [PDF·yr]
Freshwater eutrophication	Helmes et al. (2012) Azevedo (2014) Midpoint: [kg P-eq] Endpoint: [Species·yr]	Helmes et al. (2012); Tirado-Seco (2005) Midpoint: [kg PO_4 P-lim eq] Endpoint: [PDF·m^2·yr]	Helmes et al. (2012) Azevedo et al. (2013b) Azevedo et al. (2013c) Endpoint: [PDF·yr]
Marine eutrophication	Cosme & Hauschild (2017) Cosme et al. (2015) Midpoint: [kg N-eq] Endpoint: [Species·yr]	Roy et al. (2012b) Midpoint: [kg N-lim eq] Endpoint: [PDF·m^2·yr]	Cosme et al. (2015) Cosme & Hauschild (2016) Cosme & Hauschild (2017) Cosme et al. (2018) Endpoint: [PDF·yr]
Photochemical ozone formation	van Zelm et al. (2016) Midpoint: [kg NO_x -eq] Endpoint: [Species·yr]	van Zelm et al. (2016) Midpoint: [kg NO_x -eq] Endpoint: [PDF·m^2·yr]	van Zelm et al. (2016) Endpoint: [PDF·yr]
Land use / Land transformation and occupation / Land stress	de Baan et al. (2013) Elshout et al. (2014) Midpoint:	de Baan et al. (2013) Curran et al. (2010) Midpoint:	Chaudhary et al. (2015)

	[m^2 annual crop-eq] Endpoint: [Species·yr]	[m^2 arable land-eq] Endpoint: [PDF·m^2·yr]	Endpoint: [PDF·yr]
Marine ecotoxicity	van Zelm et al. (2009) van Zelm et al (2013) (USES-LCA 2.0) Midpoint: [1,4-DCB eq] Endpoint: [Species·yr]	Rosenbaum et al. (2008) Hauschild & Wenzel (1998) (USEtox (mixed species with freshwater)) Endpoint: [PDF·m^2·yr]	Rosenbaum et al. (2008) Rosenbaum et al. (2011) Henderson et al. (2011) (USEtox + marine specific data (IUCN)) Endpoint: [PDF·yr]
Terrestrial ecotoxicity	van Zelm et al. (2009, 2013) (USES-LCA 2.0) Midpoint: [1,4-DCB eq] Endpoint: [Species·yr]	Rosenbaum et al. (2008) Jolliet et al. (2003) (USEtox + Hauschild and Wenzel (1998) Endpoint: [PDF·m^2·yr]	Rosenbaum et al. (2008) Rosenbaum et al. (2011) Henderson et al. (2011) (USEtox + Owsianiak et al. (2013)) Endpoint: [PDF·yr]
Freshwater ecotoxicity	van Zelm et al. (2009, 2013) (USES-LCA 2.0) Midpoint: [1,4-DCB-eq] Endpoint: [Species·yr]	Hauschild et al. (2008) Rosenbaum et al. (2008) Jolliet et al. 2003 (USEtox) Endpoint: [PDF·m^2·yr]	Rosenbaum et al. (2008) Rosenbaum et al. (2011) Henderson et al (2011) (USEtox) Endpoint: [PDF·yr]
Plastic physical effects on biota	-	Corella-Puertas et al. (2023) Endpoint: [PDF·m^2·yr]	-
Ionizing radiation	-	Garnier-Laplace et al. (2008) Endpoint: [PDF·m^2·yr]	-
Fisheries impact	-	Stanford-Clark et al. (2024) Endpoint: [PDF·m^2·yr]	-
Thermally polluted water	-	Verones et al. (2010) Endpoint: [PDF·m^2·yr]	-

In Table 23, a summary of the evaluation of the packages can be seen. The number of impact categories is a bit inconsistent for ReCiPe 2016 and IMPACT World+. ReCiPe 2016 contains

10 endpoints, but as explained in Section 4.2, two of the impact categories has been divided into two parts, which gives a total number of 12 impact categories when producing results in e.g. OpenLCA.

IMPACT World+ contains 17 endpoint categories. In Table 22, 16 impact categories can clearly be identified. However, the package is dividing land transformation and land occupation into two different impact categories, giving a total of 17. In addition to this, when using OpenLCA, the package divides water availability into two categories, as mentioned in Section 4.3, while also excluding the impact category plastic physical effect on biota. It is unclear why this is excluded in this software.

Table 23. A summary of the evaluation of the methods

	ReCiPe 2016	**IMPACT World +**	**LC-IMPACT**
Number of impact categories related to ecosystem quality	10 midpoints 10 endpoints	8 midpoints 17 endpoints (damage level)	10 endpoints
Available in OpenLCA?	Yes, free of charge	Yes, free of charge	Yes, for a license fee
Is the method regionalized?	No	Yes	Yes

4.6 Case study and contribution analysis

In this section, the results from the case study are presented. As stated earlier, the studied material is nickel sulfate, and a global data set for the market production of nickel sulfate has been applied. The function unit is 1kg of nickel sulfate. Figure 8 and 9 illustrates the results on endpoint level for ReCiPe 2016 and IMPACT World+, respectively, in the form of a contribution analysis. Given the large number of impact categories, those contributing to less than 3% to the total impact were grouped together under the label “other” for clarity and readability. The full results can be found in Appendix A. The impact categories have been color-coded for improved readability.

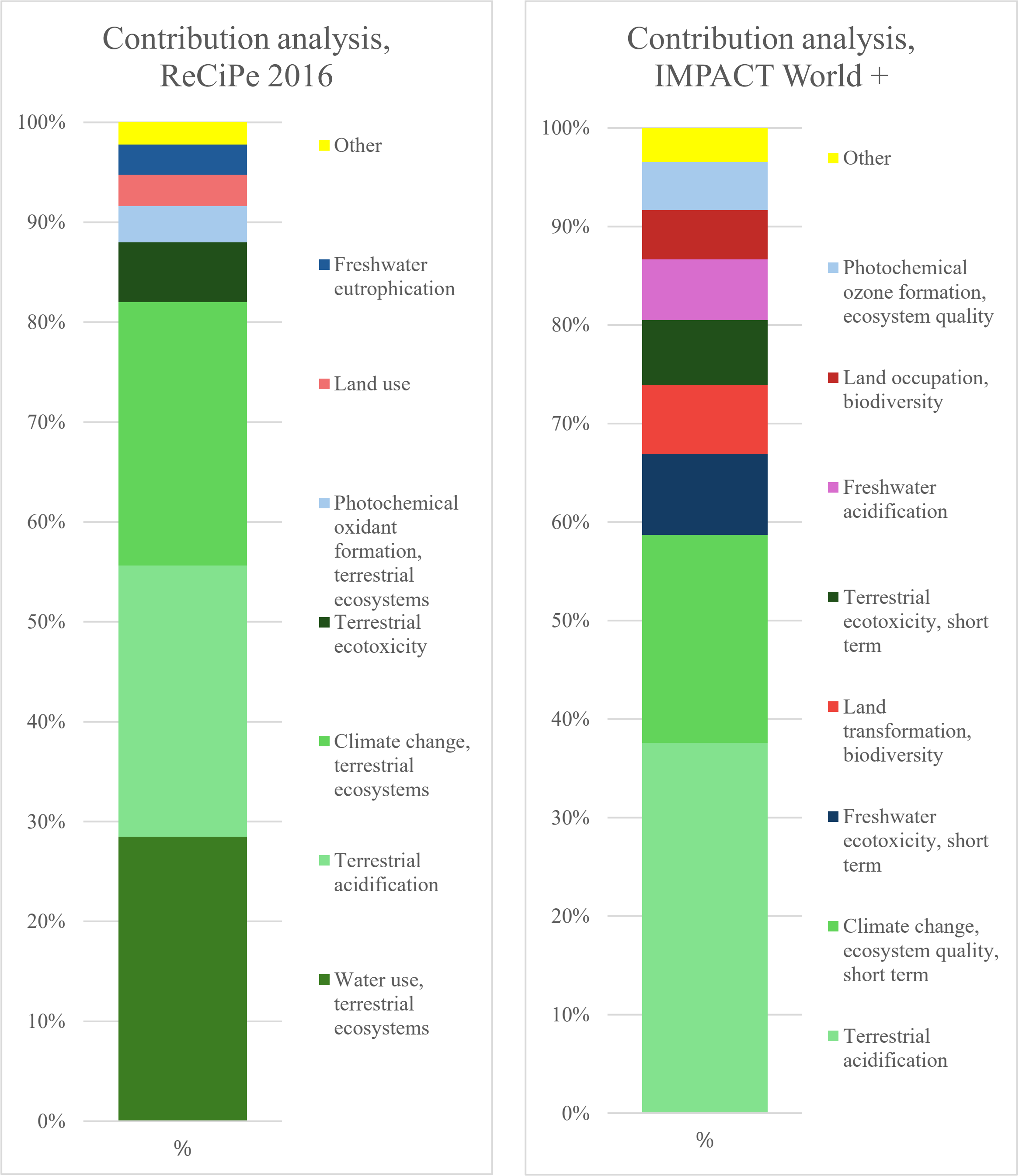

Figure 8 and 9. Results of the contribution analysis for ReCiPe 2016 and IMPACT World +.

4.7 Sensitivity analysis

In this section, the results from the sensitivity analysis are presented. As stated in the method section, the electricity mix has been switched from a global to an Indonesian and Canadian, respectively. These results are compared with the original case. Given the large number of impact categories, those contributing to less than 3% of the total impact were grouped together under the category “other” for clarity and readability. The results are shown in Figure 10 and 11, in the LCIA packages respective unit. Under each diagram, the results are shown in tables with the numerical values and the percentual change from the original case.

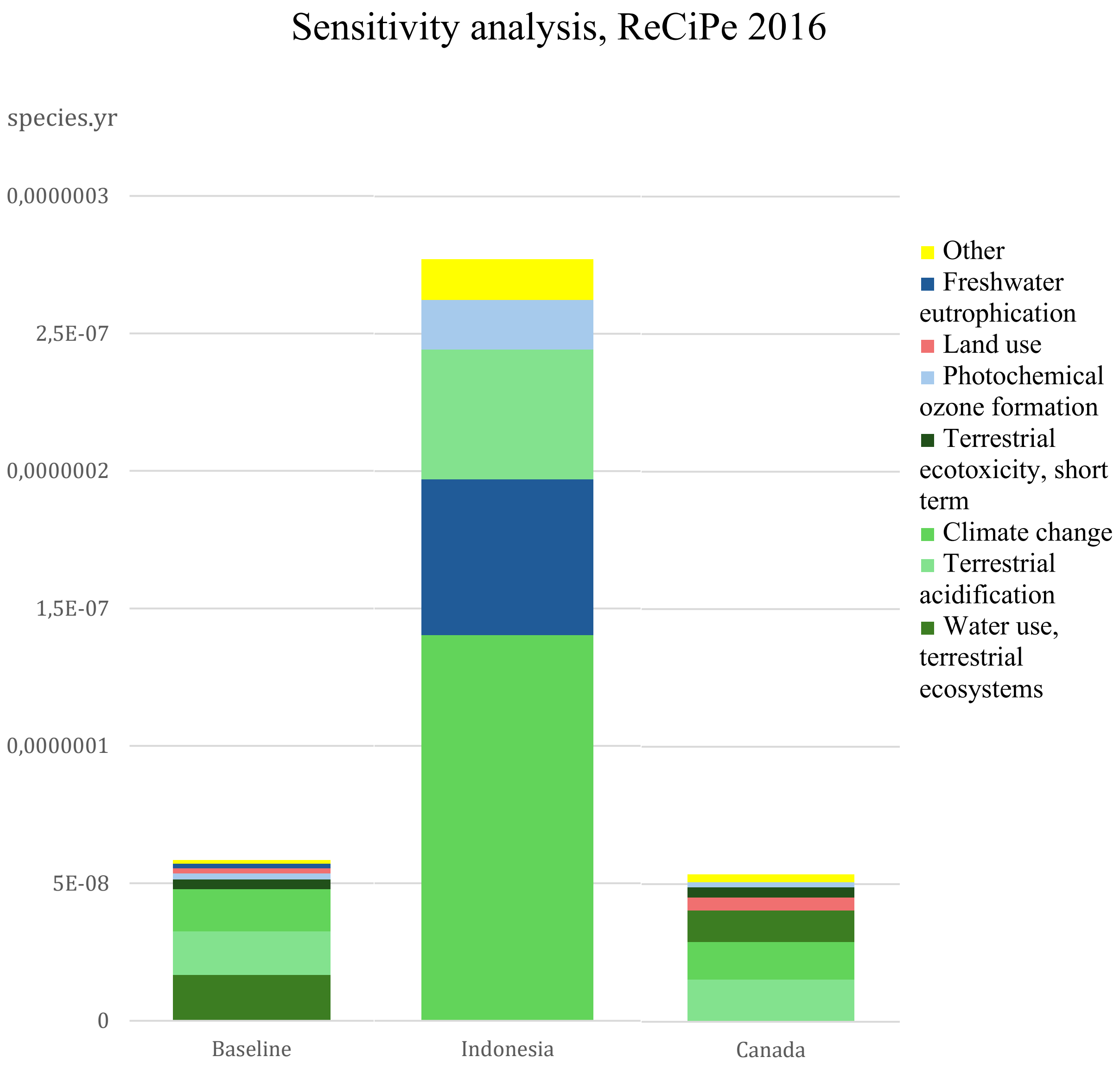

Figure 10. Results from the sensitivity analysis for ReCiPe 2016 with different electricity mixes.

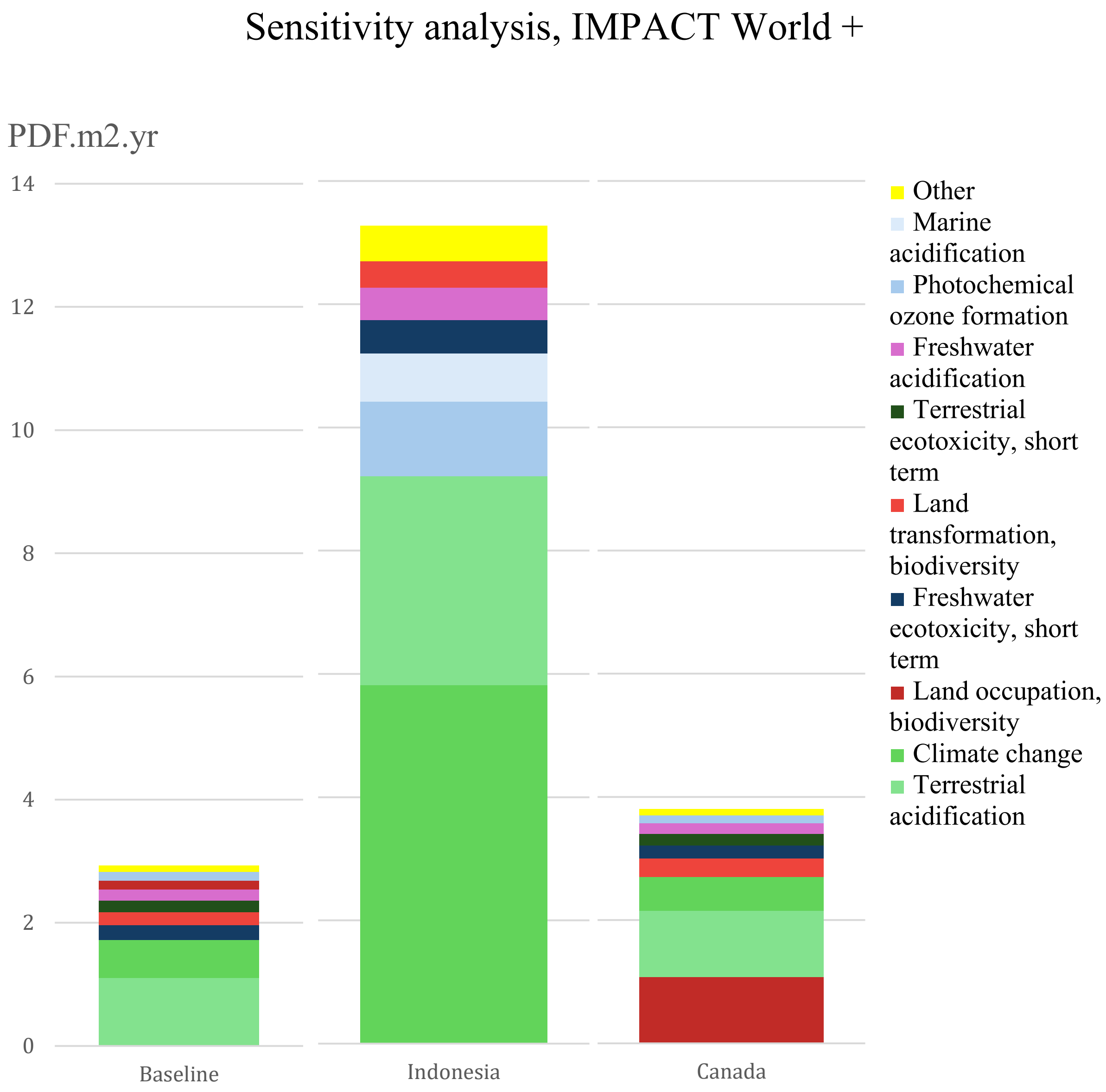

Figure 11. Results from the sensitivity analysis for IMPACT World + with different electricity mixes, in the unit PDF·m^2·yr.

5 Discussion

For clarity and readability, this chapter has been divided into six parts. These are the analysis of the packages, the implications of the case study, further research, reflections on sustainability and ethical considerations, implications for a car manufacturer, and limitations.

5.1 Analysis of the packages

The three studied LCIA packages include different impact categories. On endpoint level, ReCiPe 2016 has ten, LC-IMPACT has ten, and IMPACT World+ has 17. The high number of impact categories in IMPACT World+ can be seen as a strength, as it allows for a more comprehensive assessment of all environmental impacts. It can capture more pressures on ecosystems, which may be overlooked in the other LCIA packages. However, this broad range of impact categories can lead to a more complex analysis, which is difficult to interpret and may also be hard to effectively communicate to stakeholders. An effort was made to make this communication easier in the contribution analysis, by grouping the small impact categories together into one category called “other”. This raises a trade-off between comprehensiveness and clarity. While detailed results may show a scientific robustness, excessive complexity can reduce their usability in decision making, especially in companies where not every decision maker is an environmental expert. In addition, newer impact categories added in IMPACT World+ may be less mature in terms of model development and data coverage. For example, when looking at IMPACT World+ in OpenLCA and the newer impact category “fisheries impact”, only two contributing resource flows are considered (see Appendix). This is a stark contrast to other more established impact categories like climate change or freshwater acidification, which includes hundreds of contributing flows. The impact category primarily accounts for biomass extraction of fish from the ocean, but other factors that may affect the population, such as chemical emissions or habitat disruptions, are not yet included.

Both IMPACT World+ and LC-IMPACT are characterized by their utilization of regionalized CFs. This enables more site-specific assessments of environmental impacts, which can be helpful in understanding the environmental impacts of a certain process that takes place in different locations. In contrast, ReCiPe 2016 is using global average CFs, and therefore does not account for regional environmental sensitivities. Regionalized CFs are relevant since they tell that one process could be more demanding on the ecosystem in one region than another. For example, the land transformation process “transformation, to permanent crop” in IMPACT World+ gives a CF of 42 PDF·m^2·yr for Indonesia, and 8 PDF·m^2·yr for the US. This means that if the inventory data is the same, a five times higher endpoint result will be obtained for Indonesia compared to the US. Using these regionalized CFs can be more relevant than global ones since the environmental conditions, such as ecosystem vulnerability and species richness, can vary from one region to another. Using regionalized CFs can therefore make the results more realistic and accurate.

However, the benefit of site-specific LCIA packages like IMPACT World+ and LC-IMPACT are dependent on the availability of site-specific data. If no regionalized datasets are available, global CFs will be applied anyway. In this report, nickel sulfate was chosen as the material studied in the case study. Ecoinvent offered one market dataset for this, called “market for nickel sulfate | nickel sulfate | Cutoff U”, with two underlying datasets called “cobalt production | nickel sulfate | Cutoff, U – GLO” and “nickel sulfate production | nickel sulfate |

Cutoff, U – GLO". The geography of both these datasets is global, so no site-specific CFs were applied in any of the methods. Efforts were made to find datasets for local productions in the biggest nickel-producing countries, such as Indonesia, but no such dataset were found. Finding site-specific data turned out to be a big challenge. Some site-specific data, such as the electricity mix for specific countries, were available. However, simply replacing the global average electricity with the regional in the dataset was considered insufficient, since the electricity consumption in the nickel sulfate production process may vary between different locations. To truly be able to utilize the regional CFs, regional data is needed for products such as nickel sulfate.

Some interesting differences can be observed between the modeling in the different LCIA packages studied. In ReCiPe 2016, all the impact categories can be calculated both on midpoint and endpoint level. Once the midpoint level is calculated, a conversion factor is used to reach the endpoint. In contrast, IMPACT World+ uses a more branched approach, where midpoint indicators do not always lead into a corresponding endpoint and are not always conceptually aligned. For example, for water-related impacts, IMPACT World+ uses the water scarcity AWARE model for the midpoint level, while they use several other sources to reach the damage level. These are not on the same cause-effect chain. This can make the interpretation a bit difficult.

Another interesting modeling-related point is the use of the VS in LC-IMPACT. The methods do provide a general equation for deriving the CFs at endpoint, which includes FF, XF, EF and VS. However, it is immediately pointed out that the VS is excluded in some impact categories, which is also apparent when examining the modeling of each impact category. This points out a lack of methodological coherence in that package.

5.2 Implications of the case study

In the nickel case study, the results showed large contributions to the total score from terrestrial acidification and climate change for both ReCiPe 2016 and IMPACT World+. Starting with terrestrial acidification, this impact is primarily driven by emissions of acidifying substances such as SO_2 and NO_x, which is often linked to combustion processes in energy production and industrial activities. In the sensitivity analysis, terrestrial acidification remains a key contributor regardless of scenario. While the absolute values of terrestrial acidification increase significantly in the Indonesian electricity mix scenario, largely due to the coal-dependent electricity mix, its relative contribution to the total impact remains substantial across scenarios and LCIA packages. The CFs for terrestrial acidification are based on the research by Roy et al. (2014) for all of ReCiPe 2016, IMPACT World+ and LC-IMPACT. This indicates a broad consensus for this specific impact category.

Climate change also showed a consistently large contribution in both the contribution analysis and sensitivity analysis. Across the different electricity scenarios, the relative changes between the LCIA packages were also comparable, indicating a robust and stable response to variations in the input. The CFs for all three LCIA packages are based on similar sources, such as the IPCC report. ReCiPe 2016 and LC-IMPACT are using GWP for endpoint level, while IMPACT World + is using aGTP. The modeling is thereby a bit different, but the underlying climate data is the same, the packages just apply it differently. This can however still influence the result.

The largest impact category for ReCiPe 2016 was water use. In IMPACT World+, the same high contribution for water related impacts cannot be seen. The impact category water availability has instead been placed among "other", only accounting for 0.04% of total impact. Even if both impact categories are about water use, they are measuring different parameters. In ReCiPe 2016, water use is referring to how much water is withdrawn and consumed from watersheds. While this is relatively simple to quantify, it does not consider whether the water is taken from a water-rich or water-scarce region. Impacts could be more severe in a water-scarce region. In IMPACT World+, the water related impact category is called water availability. This looks at water scarcity and competition in specific regions. Even though the impact categories are related, they are measuring different things, which explains the different results. LC-IMPACT focuses on how the availability of water changes, with changes of the area of wetlands as a representation. All of these measurements could be useful, but it is important to understand that they are not measuring the same thing.

Freshwater eutrophication in the Indonesian ReCiPe 2016 scenario showed the largest percentual increase in the sensitivity analysis, rising by more than 3000% compared to the baseline. In contrast, the corresponding scenario using IMPACT World+ only showed a modest increase of 1.8%. Upon closer examination, it was found that the primary driver behind this increase using ReCiPe 2016 was the emission of phosphate from the treatment of spoil from lignite mining, something widely used in the Indonesian electricity mix. The phosphate flow is categorized under Elementary flows/Emissions to water/ground water, long term. In ReCiPe 2016, this flow is assigned a CF of 2.21E-7 species·yr, meaning it contributes directly to biodiversity loss. However, in IMPACT World+, the same flow is assigned a CF of 0 PDF·m^2·yr, effectively excluding its impact in the calculation. Thus, a clear difference arises in how phosphorous flows are treated in the two LCIA packages. Upon further examination, IMPACT World+ has assigned all flows to groundwater, regardless of impact category, with a CF of 0. It is not fully explained why this decision was made for all impact categories, but for ecotoxicity it is explained by limitations in the USEtox model, which the impact category is based on (IMPACT World+, n.d-b). It is, however, surprising that the CFs are so different, especially for freshwater eutrophication, since the methods are based on the same underlying research. Using a zero-value risks underestimating the actual impact. This finding highlights methodological differences, and the importance of understanding how various LCIA methods handle specific emissions, as this can significantly influence the outcomes of the LCA.

Land occupation in the Canadian IMPACT World+ scenario showed a considerable increase compared to the other impact categories in the sensitivity analysis. Thermally polluted water was also an impact category that increased notably, which in turn can be connected to the different electricity mixes between the two cases. The electricity mix in Canada is dominated by hydro- and nuclear power, in contrast to Indonesia's utilization of more carbon-intensive energy. Hydropower requires a lot of land, especially when it comes to the construction and land occupation of large reservoirs and dams. This difference can possibly give an explanation to the increased land use, which is also reflected in the ReCiPe 2016 scenario. The increase in thermally polluted water was also due to the use of hydropower, even though IMPACT World+ primarily mentions nuclear power as the contributing factor. This indicates that while the use of hydropower could help decrease impacts such as climate change, it still has other environmental effects to consider.

Many sources highlight loss of habitat as a big, if not the biggest, threat to biodiversity (Jaureguiberry et al. 2022; IPBES, 2019). In this case study, land use constitutes a rather small contribution compared to other impact categories for both LCIA packages. Both LCIA packages have based their land use impact assessment method on the work of de Baan et al. (2013), which is one of the earlier attempts to quantify land use impacts on biodiversity in LCA. De Baan et al. (2013) emphasize in their conclusion that much data gaps and uncertainty is present in the development of these CFs, and that they should serve as a first screening and not definite results. LC-IMPACT contains the work from Chaudhary et al. (2015) for their land use impact category, which is based on the work from de Baan et al. (2013). This work includes updated data and address shortcomings such as adding more ecoregions and land use types to their model. Unfortunately, LC-IMPACT was not included in the case study because of the license fee in OpenLCA. For future work, it would be interesting to investigate if this update influences the results for land use. Newer work based on the paper by de Baan et al. (2013) and Chaudhary et al. (2015) has been developed, one being a paper by Sherer et al. (2023). Here, factors such as land use intensities and habitat fragmentation have been taken into consideration. The papers by de Baan et al. (2013) and Chaudhary et al. (2015) are primarily focused on species richness and overlook the genetic and ecological diversity. The newer paper by Sherer et al. (2023) takes genetic diversity into consideration by considering fragmentation. If populations become trapped in smaller habitats without connections to others, there is a higher risk of inbreeding. Since this newer approach is not implemented in any of the LCIA packages studied in this thesis, it is difficult to determine how it would influence the results.

Another important aspect in land use is the choice of reference situation. For both ReCiPe 2016 and IMPACT World+, which are based on the work from de Baan et al. (2013), the reference situation is based on late succession, referring to what the ecosystem in a certain place would look like if all human activities ended. The time to reach this state differs between regions. It could be argued that using a pristine, pre-disturbance conditions as a reference instead might be a better choice. Such baseline could reflect the full ecological potential of the area and capture the total biodiversity loss caused by land use. However, this approach also comes with some challenges, such as deciding the pristine state in already altered landscapes.

5.3 Further research

Biodiversity is a very broad concept, which includes many aspects and parameters, and is therefore hard to capture with a single measure or indicator. It includes genetic, species and ecological diversity. The LCIA packages evaluated in this report include many important contributions to ecosystem damage, but some more aspects could still be added in future developments. One example is invasive species, which to the best of our understanding is yet to be accounted for. In addition, some species may be keystone or foundation species and have more important roles to play in the ecosystem as a whole, which is also not accounted for. The range of species accounted for could also be improved and expanded to consider more insects, which is a species group that is essential for an ecosystem. It is difficult for an LCIA method to be able to cover everything that the concept biodiversity contains. However, considering more factors that arguably influence biodiversity, such as fragmentation, could lead to more comprehensive results.

In the context of LCIA, many LCIA packages aggregate biodiversity into one single unit, such as potentially disappeared fraction of species (PDF), species loss and species richness change. In the context of biodiversity, all these focuses more on species diversity than other types of diversity. Using endpoints and translating all impact categories into the same unit is a simplification in order to make the impact categories more comparable. This can make it easier for stakeholders and researchers to spot which impacts are high and low. However, it is also important to reflect on how these translations are made. Different impact categories, such as climate change and acidification, affect ecosystems through different mechanisms that operate over different spatial and temporal scales. When translating these into the same unit, there are modeling choices and assumptions that play a role, possibly impacting the outcome. An impact category can therefore be both under- and overrepresented. This simplification makes the impact categories more comparable, which is positive, but it is also important to note that some impact categories, especially in IMPACT World+, are quite new and may not be as developed as the others, therefore not providing as reliable results.

5.4 Reflections on sustainability and ethical considerations

This thesis is mainly rooted in the environmental dimension of sustainable development, with a focus on how different LCIA packages assess and capture biodiversity. However, biodiversity loss also has significant impacts on both the social and economic dimensions, as it effects food security, livelihoods and ecosystem services, among other things. When biodiversity is lost, these services get weakened, with especially severe consequences for communities and individuals that rely closely on nature for their livelihood. Thus, for more people and stakeholder to understand the severity of the problem, it is important to underline that biodiversity loss is not only about non-human species and their wellbeing, but that it has consequences for humans as well.

How one values biodiversity comes down to ethics. Most LCIA packages rely on an anthropocentric view, meaning that they assess the environmental impacts based on how they affect human well-being. However, this perspective is not always clearly communicated in LCIA. In the case of ecosystem quality, the focus is often on species loss, with no further explanations of how these losses can directly, or indirectly, affect people and communities. Without a deeper understanding of the underlying methods leading up to the endpoint results, it can be easy to interpret the results as only being about saving species, rather than understanding the broader consequences for human well-being. For some, it can make these impacts distant and less relevant than those connected to i.e. human health. LCIA results may be interpreted through other ethical standpoints, such as zoocentrism, biocentrism or ecocentrism. However, many people, especially those in decision-making positions such as at profit-driven companies, may primarily hold an anthropocentric view. Regardless of what ethical standpoint one holds, it is important to acknowledge that not everyone may hold the same. If the human relevance related to biodiversity is not emphasized, it could risk the results being overlooked or deprioritized, especially by those holding an anthropocentric viewpoint.

5.5 Implications for a car manufacturer

It is important for car manufacturers to keep track of their environmental impacts. Even if electrical cars is considered a solution for CO_2 emissions in the use phase, it is important to acknowledge other environmental aspects this shift may entail. LCIA can be a helpful tool when comparing different materials, especially early in the design phase. It can give a good indication of which material have a higher environmental impact, and why. The case study in this thesis was made for 1 kg of nickel sulfate. If wanting to see the full impacts, scaling up each material to the amount used in the battery would be necessary. This could further help to see if making changes to the composition of the battery would have any impact, and how large. Using a sensitivity analysis could also help in the understanding of how changes to certain processes, such as the electricity use, affects the results.

When it comes to biodiversity, no LCIA package currently captures the full definition. Most of the impact categories are focused on species richness, while other important factors such as keystone species and genetic diversity are left out. Even though LCIA is a strong tool, in its current state it cannot be the only approach used if a company wants to fully understand their impacts on biodiversity. One example is the effect on genetic diversity when building a road through a habitat. This does not just occupy land, it can also split animal populations in half, increasing the risk of inbreeding and reduction of genetic diversity. Since this is currently not captured in the LCIA packages studied, it is important to investigate how one could facilitate the movement of the animals, e.g. building wildlife overpasses.

5.6 Limitations

Not all currently existing LCIA packages were considered and evaluated in this study, as they did not live up to the set criteria in Section 3.1. Some LCIA packages found during the literature study were excluded since they did not meet the criteria. The package had to include ecosystem quality as an area of protection, utilize endpoints, have sufficient documentation and be available to use in LCA software programs. This led to only the LCIA packages met the criteria being evaluated in detail. LCIA packages that were found interesting but did not fit the criteria were Product Environmental Footprint (PEF), Environmental Priority Strategies (EPS) and GLAM. The PEF method was not inlcuded because of the method's lack of endpoint indicators, which would make it difficult to compare the results to each other. The EPS method was considered because it translates all environmental and resource impacts into economic value, thus leaning more towards being a weighting method. This would also make it difficult to compare the results with those from other LCIA packages that utilize endpoints. The GLAM package would have been evaluated and studied in detail if the existing information and documentation would have been more coherent and available. The planned release to LCA software was postponed, which made it hard to do a case study on GLAM.

6 Conclusion

This study has analyzed how the LCIA packages ReCiPe 2016, IMPACT World+ and LC-IMPACT, represent impacts on the natural environment, with particular focus on biodiversity. The results showed that while all three methods include biodiversity-related endpoint indicators, they differ in impact categories included, underlying characterization methods for these impact categories and impact pathways considered. As demonstrated in the case study, this influences the end result, even when using the same inventory data.

Notably, IMPACT World+ includes a broader set of impact categories than the other two LCIA packages. This could offer a more comprehensive understanding of all the impacts on ecosystems. However, some of the underlying LCIA methods are new and might not be as scientifically robust as those that have been used for longer time in the LCIA field. The LCIA packages do use regionalization, but without site-specific data it cannot be properly utilized.

ReCiPe 2016 is currently used by the car company. It offers a clear and structured approach with both midpoint and endpoint indicators. However, the lack of regional CFs can limit its accuracy in location specific assessments, which is important given the wide variation of ecosystems on Earth, with different abilities to handle environmental pressures.

LC-IMPACT was introduced in 2020, developed to improve spatial accuracy. It focuses solely on endpoint indicators. While it enhances geographical accuracy, it may reduce the flexibility for users who prefer midpoint-level insights for making decisions at earlier stages.

The case study helped highlighting both similarities and differences between two of the LCIA packages. Seeing large differences in the results helped indentifying and exploring why they varied, for example in their use of characterization factors and impact pathways. The sensitivity analysis further demonstrated how changes in the inventory data affected the result. This could be especially helpful for the understanding of the environmental impacts of different electricity sources.

Based on these findings, it is clear that no single package currently offers a fully comprehensive approach to assessing biodiversity impacts. Each method has its strengths and limitations, and ongoing research continues to refine how biodiversity impacts are captured within LCA. All LCIA packages' focus is on species diversity, with less focus on other types and elements of biodiversity, such as genetic diversity and keystone species.

It is recommended to stay informed about ongoing methodological development, especially in areas where there is a lack of consensus on which research/method the impact category is based on, such as land use and water use. Applying multiple methods, as well as conducting sensitivity analysis for uncertain data, may also help the company to strengthen the reliability of biodiversity-related conclusions in their assessments. This may be more time-consuming but can result in more robust results and insights.

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Appendix A

A.1 Results of the case study and contribution analysis

Table A1.1. Results of the case study for ReCiPe 2016.

Impact category	**Result**	**Reference unit**
Climate change, freshwater ecosystems	4,209E-13	species.yr
Climate change, terrestrial ecosystems	1,541E-08	species.yr
Freshwater ecotoxicity	1,063E-09	species.yr
Freshwater eutrophication	1,790E-09	species.yr
Land use	1,810E-09	species.yr
Marine ecotoxicity	2,198E-10	species.yr
Marine eutrophication	2,394E-12	species.yr
Photochemical oxidant formation, terrestrial ecosystems	2,121E-09	species.yr
Terrestrial acidification	1,587E-08	species.yr
Terrestrial ecotoxicity	3,525E-09	species.yr
Water use, aquatic ecosystems	7,456E-13	species.yr
Water use, terrestrial ecosystems	1,667E-08	species.yr
Total	5,848E-08	species.yr

Table A1.2. Results of the contribution analysis for ReCiPe 2016.

Impact category	**Fraction**
Water use, terrestrial ecosystems	0,285
Terrestrial acidification	0,271
Climate change, terrestrial ecosystems	0,263
Terrestrial ecotoxicity	0,060
Photochemical oxidant formation, terrestrial ecosystems	0,036
Land use	0,031
Freshwater eutrophication	0,031
Freshwater ecotoxicity	0,018
Marine ecotoxicity	0,004
Marine eutrophication	0,000
Water use, aquatic ecosystems	0,000
Climate change, freshwater ecosystems	0,000
Total	1

Table A1.3. Results of the case study for IMPACT World+.

Impact category	**Result**	**Reference unit**
Climate change, ecosystem quality, short term	0,619	PDF.m2.yr
Fisheries impact	0,000	PDF.m2.yr
Freshwater acidification	0,180	PDF.m2.yr

Freshwater ecotoxicity, short term	0,242	PDF.m2.yr
Freshwater eutrophication	0,006	PDF.m2.yr
Ionizing radiations, ecosystem quality	0,000	PDF.m2.yr
Land occupation, biodiversity	0,147	PDF.m2.yr
Land transformation, biodiversity	0,205	PDF.m2.yr
Marine acidification, short term	0,075	PDF.m2.yr
Marine ecotoxicity, short term	0,000	PDF.m2.yr
Marine eutrophication	0,017	PDF.m2.yr
Photochemical ozone formation, ecosystem quality	0,143	PDF.m2.yr
Terrestrial acidification	1,102	PDF.m2.yr
Terrestrial ecotoxicity, short term	0,193	PDF.m2.yr
Thermally polluted water	0,002	PDF.m2.yr
Water availability, freshwater ecosystem	0,000	PDF.m2.yr
Water availability, terrestrial ecosystem	0,001	PDF.m2.yr
Total	2,931711	PDF.m2.yr

Table A1.4. Results of the contribution analysis for IMPACT World+.

Impact category	**Fraction**
Terrestrial acidification	0,376
Climate change, ecosystem quality, short term	0,211
Freshwater ecotoxicity, short term	0,083
Land transformation, biodiversity	0,070
Terrestrial ecotoxicity, short term	0,066
Freshwater acidification	0,061
Land occupation, biodiversity	0,050
Photochemical ozone formation, ecosystem quality	0,049
Marine acidification, short term	0,026
Marine eutrophication	0,006
Freshwater eutrophication	0,002
Thermally polluted water	0,001
Water availability, terrestrial ecosystem	0,000
Water availability, freshwater ecosystem	0,000
Marine ecotoxicity, short term	0,000
Ionizing radiations, ecosystem quality	0,000
Fisheries impact	0,000
Total	1

A.2 Changes made for the sensitivity analysis

Table A2.1. Changes made in the sensitivity analysis for the case with the Indonesian electricity mix.

Original process name	New process name	Changed from in the original process	Changed to in the new process

Market for nickel sulfate | nickel sulfate | Cutoff U - GLO	Market for nickel sulfate | nickel sulfate | Cutoff U (copy) – ID	**Flow:** nickel sulfate **Provider**: cobalt production | nickel sulfate | Cutoff U - GLO **Flow:** nickel sulfate **Provider**: nickel sulfate production | nickel sulfate | Cutoff, U - GLO	**Flow:** nickel sulfate **Provider**: cobalt production | nickel sulfate | Cutoff U (copy) – ID **Flow:** nickel sulfate **Provider**: nickel sulfate production | nickel sulfate | Cutoff, U (copy) - ID
cobalt production | nickel sulfate | Cutoff U	cobalt production | nickel sulfate | Cutoff U (copy) - ID	**Flow**: electricity, medium voltage, cobalt industry **Provider**: market for electricity, medium voltage, cobalt industry | electricity, medium voltage, cobalt industry | Cutoff, U - GLO	**Flow**: electricity, medium voltage - ID **Provider**: market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - ID
nickel sulfate production | nickel sulfate | Cutoff, U	nickel sulfate production | nickel sulfate | Cutoff, U (copy) - ID	**Flow:** electricity, medium voltage - ID **Provider:** market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO	**Flow:** electricity, medium voltage - ID **Provider**: market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - ID

Table A2.2. Changes made in the sensitivity analysis for the case with the Canadian electricity mix.

Original process name	New process name	Changed from in the original process	Changed to in the new process
Market for nickel sulfate | nickel sulfate | Cutoff U - GLO	Market for nickel sulfate | nickel sulfate | Cutoff U (copy) – Can	**Flow:** nickel sulfate **Provider**: cobalt production | nickel sulfate | Cutoff U - GLO **Flow:** nickel sulfate **Provider**: nickel sulfate production | nickel sulfate | Cutoff, U - GLO	**Flow:** nickel sulfate **Provider**: cobalt production | nickel sulfate | Cutoff U (copy) – Can **Flow:** nickel sulfate **Provider**: nickel sulfate production | nickel sulfate | Cutoff, U – Can
cobalt production | nickel sulfate | Cutoff U	cobalt production | nickel sulfate | Cutoff U (copy) - Can	**Flow**: electricity, medium voltage, cobalt industry **Provider**: market for electricity, medium voltage, cobalt industry | electricity, medium voltage, cobalt industry | Cutoff, U - GLO	**Flow**: electricity, medium voltage **Provider**: market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – CA-QC
nickel sulfate production |	nickel sulfate production | nickel	**Flow:** electricity, medium voltage - ID	**Flow:** electricity, medium voltage

nickel sulfate | Cutoff, U	sulfate | Cutoff, U (copy) - Can	**Provider:** market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO	**Provider**: market for electricity, medium voltage | electricity, medium voltage | Cutoff, U – CA-QC

A.3 Results of the sensitivity analysis

Table A3.1. Results of the sensitivity analysis for Indonesian electricity mix and ReCiPe 2016, with the percentual change from the baseline case.

Impact category	**Baseline**	**Indonesia**	**Difference**
Climate change, freshwater ecosystems	4,209E-13	3,835E-12	811,2%
Climate change, terrestrial ecosystems	1,541E-08	1,404E-07	811,1%
Freshwater ecotoxicity	1,063E-09	2,477E-09	133,1%
Freshwater eutrophication	1,790E-09	5,664E-08	3064,7%
Land use	1,810E-09	4,580E-09	153,0%
Marine ecotoxicity	2,198E-10	5,159E-10	134,7%
Marine eutrophication	2,394E-12	1,114E-11	365,4%
Photochemical oxidant formation, terrestrial ecosystems	2,121E-09	1,792E-08	745,2%
Terrestrial acidification	1,587E-08	4,740E-08	198,6%
Terrestrial ecotoxicity	3,525E-09	3,746E-09	6,3%
Water use, aquatic ecosystems	7,456E-13	1,542E-13	-79,3%
Water use, terrestrial ecosystems	1,667E-08	3,446E-09	-79,3%
Total	5,848E-08	2,771E-07	373,9%

Table A3.2. Results of the sensitivity analysis for Canadian electricity mix and ReCiPe 2016, with the percentual change from the baseline case.

Impact category	**Baseline**	**Canada**	**Difference**
Climate change, freshwater ecosystems	4,209E-13	3,709E-13	-11,9%
Climate change, terrestrial ecosystems	1,541E-08	1,358E-08	-11,9%
Freshwater ecotoxicity	1,063E-09	1,046E-09	-1,6%
Freshwater eutrophication	1,790E-09	1,566E-09	-12,5%
Land use	1,810E-09	4,800E-09	165,1%
Marine ecotoxicity	2,198E-10	2,161E-10	-1,7%
Marine eutrophication	2,394E-12	2,319E-12	-3,1%
Photochemical oxidant formation, terrestrial ecosystems	2,121E-09	1,906E-09	-10,1%
Terrestrial acidification	1,587E-08	1,545E-08	-2,7%
Terrestrial ecotoxicity	3,525E-09	3,503E-09	-0,6%
Water use, aquatic ecosystems	7,456E-13	5,145E-13	-31,0%
Water use, terrestrial ecosystems	1,667E-08	1,150E-08	-31,0%
Total	5,848E-08	5,357E-08	-8,4%

Table A3.3. Results of the sensitivity analysis for Indoensian electricity mix and IMPACT World+, with the percentual change from the baseline case.

Impact category	**Result baseline**	**Result Indonesia**	**Difference**
Climate change, ecosystem quality, short term	0,619	5,818	840,1%
Fisheries impact	0,000	0,000	4,6%
Freshwater acidification	0,180	0,528	193,3%
Freshwater ecotoxicity, short term	0,242	0,541	123,4%
Freshwater eutrophication	0,006	0,006	1,8%
Ionizing radiations, ecosystem quality	0,000	0,000	-92,5%
Land occupation, biodiversity	0,147	0,306	108,2%
Land transformation, biodiversity	0,205	0,423	106,8%
Marine acidification, short term	0,075	0,782	937,8%
Marine ecotoxicity, short term	0,000	0,000	6,5%
Marine eutrophication	0,017	0,050	193,8%
Photochemical ozone formation, ecosystem quality	0,143	1,211	749,0%
Terrestrial acidification	1,102	3,391	207,7%
Terrestrial ecotoxicity, short term	0,193	0,205	6,5%
Thermally polluted water	0,002	0,002	-27,9%
Water availability, freshwater ecosystem	0,000	0,000	-87,2%
Water availability, terrestrial ecosystem	0,001	0,006	700,1%
Total	2,932	13,269	352,6%

Table A3.4. Results of the sensitivity analysis for Canadian electricity mix and IMPACT World+, with the percentual change from the baseline case.

Impact category	**Result baseline**	**Result Canada**	**Difference**
Climate change, ecosystem quality, short term	0,619	0,546	-11,7%
Fisheries impact	0,000	0,000	26,6%
Freshwater acidification	0,180	0,175	-2,6%
Freshwater ecotoxicity, short term	0,242	0,217	-10,4%
Freshwater eutrophication	0,006	0,006	-0,2%
Ionizing radiations, ecosystem quality	0,000	0,000	-70,7%
Land occupation, biodiversity	0,147	1,081	635,9%
Land transformation, biodiversity	0,205	0,298	45,4%
Marine acidification, short term	0,075	0,069	-9,1%
Marine ecotoxicity, short term	0,000	0,000	-3,1%
Marine eutrophication	0,017	0,016	-2,6%
Photochemical ozone formation, ecosystem quality	0,143	0,128	-10,2%
Terrestrial acidification	1,102	1,071	-2,8%
Terrestrial ecotoxicity, short term	0,193	0,187	-3,1%
Thermally polluted water	0,002	0,012	408,0%
Water availability, freshwater ecosystem	0,000	0,000	-34,0%
Water availability, terrestrial ecosystem	0,001	0,001	-2,7%
Total	2,932	3,808	29,9%

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